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# Research and Findings on Roundabouts and Innovative Intersections for High-Speed and Rural Locations

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16. Abstract

Texas has thousands of centerline-miles of high-speed roadways where access might traditionally have been restricted, but there are an increasing number of high-speed roadways that have at-grade intersections and driveways. Innovative intersection designs (e.g., j-turns, median U-turns) and modern roundabouts have been used to remove conflict points and redistribute turning traffic from traditional intersections, and their success has been documented at locations across the country. However, minimal guidance exists on using those intersection types at rural and high-speed locations, particularly to serve high volumes of heavy vehicles. This project investigated the operational and safety benefits of modern roundabouts and selected innovative intersection designs for high-speed locations, as well as best practices for designing these intersections. The research team compiled proven results from these designs in other states and collected and analyzed operational and safety data from within and outside of Texas to develop updated design guidance, which can be used to implement roundabout designs that accommodate oversize/overweight vehicles and innovative intersections that provide appropriate access in rural areas.

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# RESEARCH AND FINDINGS ON ROUNDABOUTS AND INNOVATIVE INTERSECTIONS FOR HIGH-SPEED AND RURAL LOCATIONS

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# DISCLAIMER

This research was sponsored by the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Marcus A. Brewer, P.E. #92997.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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# CHAPTER 1: INTRODUCTION

## BACKGROUND

The Texas Department of Transportation (TxDOT) operates thousands of centerline-miles of high-speed roadways, at speeds at which access might traditionally have been restricted. Because posted speed limits have increased with the repeal of the national speed limit and subsequent legislative acts, there are an increasing number of high-speed roadways that have at-grade access points—both intersections with other roads and driveways connecting to adjacent land uses. Innovative intersection designs (e.g., j-turns, median U-turns) have been used to remove conflict points and redistribute turning traffic from traditional intersections, and their success has been documented at locations across the country. However, guidance on use of innovative intersection designs and how to choose the most appropriate design from multiple alternatives is still not fully developed. Additional research would provide design guidelines based on Texas conditions for designers to make more informed decisions about the intersection design features most appropriate for a given location.

Similarly, roundabouts have documented benefits in improved operations and crash reduction in a variety of conditions nationwide. While typically used in urban and suburban environments with lower speeds, they can also be used in rural, high-speed environments when properly designed. What is less well-known is how well they perform at intersections that serve large volumes of oversize and overweight (OSOW) vehicles. The characteristics of roundabouts that facilitate the slower speeds on approach and within the intersection also can make it more challenging to navigate for a vehicle with a permit load. They have been used in other states to process traffic for distribution centers, windmill farms, and oilfield development. Roundabouts may be a useful tool in Texas to provide intersection alternatives for rural intersections that have high volumes of trucks, but additional research is needed to quantify those benefits in Texas locations.

## PURPOSE OF THE PROJECT

This project investigated the operational and safety benefits of modern roundabouts and selected innovative intersection designs for high-speed locations, as well as best practices for designing these intersection alternatives. In this project, the research team compiled proven results from these designs in other states and collected and analyzed operational and safety data within Texas to develop updated design guidance. The Receiving Agency can use this design guidance to implement roundabout designs that accommodate OSOW vehicles and innovative intersections that provide appropriate access in rural areas.

## ORGANIZATION OF THIS REPORT

This report consists of seven chapters and one appendix. In addition to this introductory chapter, the report contains the following material:

- Chapter 2 summarizes the findings from a review of existing guidance and research on roundabouts.
- Chapter 3 summarizes existing guidance and research findings on innovative intersections.
- Chapter 4 describes activities in identifying and selecting the field study sites for the roundabout study, along with a summary of data collection and microsimulation analysis and the respective findings from each.
- Chapter 5 contains a description of the key references related to innovative intersections as well as a discussion of the activities and findings related to field studies and simulation analysis.
- Chapter 6 describes activities and findings from a safety review of innovative intersections.
- Chapter 7 provides the findings and conclusions identified and developed as part of the project, along with suggestions for implementation and recommendations for future research.
- The appendix contains the recommended design guidelines for roundabouts and alternative intersections based on the review of literature and current practices in Tasks 2 and 3 as well as the findings from the field studies in Tasks 6 and 7.

# CHAPTER 2: EXISTING GUIDANCE FOR ROUNDABOUTS

This chapter summarizes the findings identifying existing guidance materials for roundabouts with high-speed approaches. The review of existing guidance included a traditional literature review, which revealed a variety of recommendations and suggestions for design elements and traffic control devices appropriate for reducing speed on approaches and for accommodating trucks and OSOW vehicles. Researchers also identified existing design guidelines and policy documents in several states and Australia, in addition to the benchmark policy document from the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP), which is commonly known as NCHRP Report 672.

## REVIEW OF EXISTING RESEARCH ON HIGH-SPEED ROUNDABOUTS

A great deal of research has been conducted on roundabouts since they were introduced in the United States roughly two decades ago. A variety of studies, reports, and guidelines can be found on the design of roundabouts, along with their associated operational and safety benefits. While those studies may provide an informational foundation that can be used for virtually any roundabout, because this project is focused on roundabouts in high-speed environments, the review described in this report will have the same focus. Literature that does not have a focus on high-speed roundabouts will have less prominence in this chapter.

### Research on Design Elements

One of the key features of modern roundabouts that makes it unique among intersection designs is its geometry that either encourages or forces slower speeds for vehicles entering and traveling through the circulatory roadway. NCHRP Report 672, which also serves as FHWA's *Roundabouts: An Informational Guide* (*1*), places the information on this key feature on the first page of its introduction. Later in the first chapter of that same document, a summary of different categories of roundabouts states that the desirable maximum entry design speed for a single lane roundabout is 20 to 25 mph, with a raised central island and a typical inscribed circle diameter of 90 to 180 ft. This entry design speed has a relatively modest transition from speeds typically found on many urban and suburban streets, which are often posted at 40 mph or lower; however, the higher speeds commonly found on rural highways necessitate a transition designed for a larger difference in speed between the approach speed and the entry design speed, which requires more deliberate consideration of appropriate design treatments and strategies to facilitate that transition.

Berloco et al. (*2*) compared methods of defining and measuring vehicle path deflection from multiple countries for the purpose of evaluating the appropriateness of the deviation angle method used in Italy and Switzerland. The deviation angle is defined in their study as the angle included between the two tangent lines to the 3.5-m (11.5-ft) offsets of the entry and exit curb radii, shown as β in Figure 1. Their research focused on a comparison between the deviation angle method, the entry path radius (or fastest path) method used in the United States (as described in [*1*]), and the German method that requires the lateral displacement of the vehicle entering the roundabout to be at least twice the approach lane width. In the Italian method, a value of β greater than or equal to 45° is recommended for each crossing leg. Their study found that the Italian method failed at roundabouts for which the angle between opposing legs was less than 140°. They concluded that the entry path radius and the German method are much less restrictive than the deviation angle method for roundabouts with non-orthogonal intersecting roads or with different entry and exit legs radii, since the deviation angle is strongly dependent on the mutual inclination of the roads and on these radii.

NCHRP Report 672, in its discussion on geometric design in Chapter 6, has caveats about considerations for larger vehicles (*1*). Because roundabouts are intentionally designed to slow traffic, narrow pavement widths and tight turning radii are typically used; however, if the widths and turning requirements are too restrictive, it can create difficulties for large vehicles. Large trucks and buses often dictate many of the roundabout's dimensions, particularly for single-lane roundabouts. Therefore, it is very important to determine the design vehicle at the start of the design and investigation process.

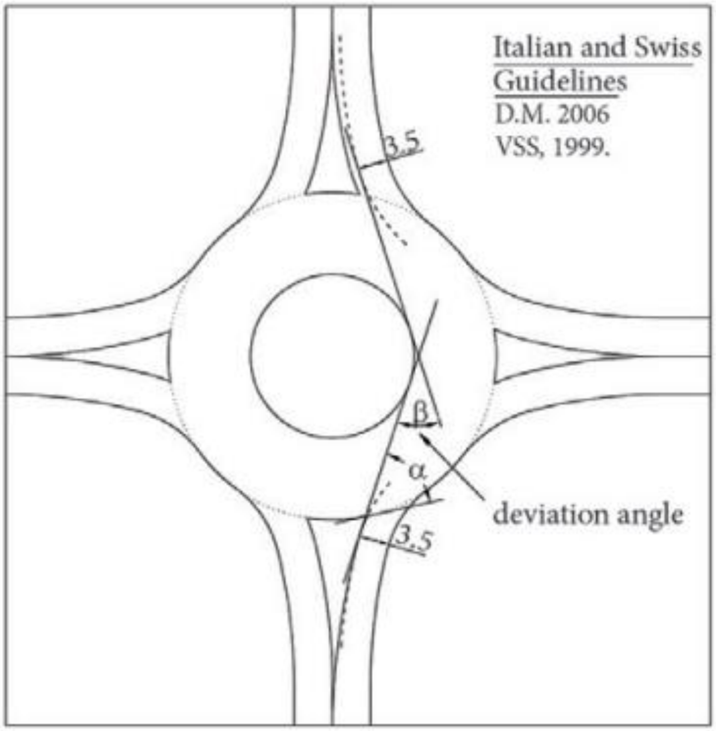



**Figure 1. Illustration of Deviation Angle (from Figure 1 in *2*).**

One example of an accommodation for a large design vehicle is a truck apron, illustrated in Figure 2. In this example, the tractor-trailer is accommodated using an apron within the central island. The apron provides additional paved surface to accommodate the wide path of the trailer, but it enables the design to keep the actual circulatory roadway width narrow enough to maintain speed control for smaller passenger cars. As shown in the photograph, the size of the roundabout also allows the cab of the truck to successfully navigate through the intersection without running over the outer curb lines. Truck aprons should be designed such that they are traversable to trucks but discourage passenger vehicles from using them. Truck apron width is dictated by the tracking of the design vehicle using templates or computer-aided design (CAD)-based vehicle-turning-path simulation software. They should generally be 3 to 15 ft wide and have a cross slope of 1 to 2 percent away from the central island. To discourage use by passenger vehicles, the outer edge of the apron should be raised approximately 2 to 3 inches above the circulatory roadway surface. The apron should be constructed of a different material than the pavement to differentiate it from the circulatory roadway. Care must be taken to ensure that delivery trucks will not experience load shifting as their rear trailer wheels track across the apron.

**Figure 2. Example of Roundabout Designed for Large Trucks (from Exhibit 6-6 in *1*).**

According to NCHRP Report 672 (*1*), WB-50 vehicles are commonly the largest vehicles along urban collectors and arterials. Larger trucks, such as WB-67 vehicles, may need to be addressed at intersections on interstate freeway or state highway systems. At a minimum, fire engines, transit vehicles, and single-unit delivery vehicles should be considered in urban areas, and it is desirable that these vehicles be accommodated without the use of the truck apron. In rural environments, farming or mining equipment may govern design vehicle needs. For locations with a high volume of truck traffic, special consideration may be given to the size of the roundabout to require use of the truck apron by only the largest of vehicles. For the example illustrated in Figure 3, the high volume of truck traffic traversing through the intersection dictated the use of a larger inscribed circle diameter. This larger diameter provides a greater ease of movement for large vehicles and minimizes the widths for the entries, exits, and circulatory roadway. While the design dimensions chosen for this roundabout were appropriate for the environmental context and design vehicle, the diameter of the roundabout should generally be kept to a minimum.

**Figure 3. Roundabout with High Volume of Heavy Vehicles (from Exhibit 6-20 in *1*).**

OSOW vehicles (sometimes referred to as “superloads”) are another potential design vehicle that may require consideration in some locations, particularly in rural areas and at freeway interchanges. These oversized vehicles occur relatively infrequently and typically require a special permit for traveling on the roadway. According to NCHRP Report 672 (*1*), roundabouts should generally not be designed to provide normal circulation using an oversized truck as the design vehicle since this will result in excessive dimensions and higher speeds for the majority of users; however, at locations where an oversized vehicle is anticipated, special consideration for the size and tolerances of these vehicles will need to be provided in the design and construction of the facility (e.g., in the truck apron and central island design).

Russell et al. (*3*) synthesized available information on the accommodation of OSOW vehicles at roundabouts. They found no published reports specifically pertaining to OSOW accommodation in their literature review; however, they did review much information (e.g., personal contacts, unpublished material, case studies, and surveys) on the advantages of having designated truck and OSOW networks. The authors concluded that vertical ground clearance in general, and curbs in particular, are a major problem for large trucks and OSOW that need to be mitigated wherever OSOW need to be accommodated. The authors further concluded that 3 inches should be considered as a maximum height of splitter islands, truck aprons, and curbs to minimize the likelihood of “hang-ups” and high-centered vehicles and trailers. Even with those caveats, however, the authors concluded, based on extensive simulation of a variety of scenarios, that, given the knowledge of accommodations needed for OSOW vehicles, any knowledgeable designer can incorporate those needs into the design, provided that right of way is available. It is up to the responsible agency to determine the economic benefits or disbenefits of doing so at a particular location.

The Russell study also obtained information through surveys to various stakeholder groups, including the freight community. The result of that interaction was a recommendation that states should consider conducting a study to develop a freight network, which includes segments where OSOW vehicles need to be accommodated, in accordance with state and federal commerce laws and policies and the state's economy. They said the recommended study should include determining all motor vehicles whose size and turning movements are critical to developing routes on which all segments will accommodate those vehicles. Specific design-related recommendations from those surveys indicated that all the following strategies have merit for accommodating OSOW vehicles:

- Wide truck aprons (12 feet or more) with a minimum slope and mountable curb.
- Customized center islands to address known left turns and support through movements. These islands may simply have truck aprons or mountable curbs to facilitate the larger turning radius of OSOW vehicles, or they may allow for movement through the middle island (perhaps by a gated path) in specific circumstances. The use of these treatments is contingent on a minimum of "hardware" in the center island.
- Paved area behind curb on the approach (right side for offtracking).
- Removable signs on setbacks for permanent fixtures (light poles).
- Allowance for trucks to cross over the splitter island before entering the roundabout in a counterflow direction to make a left turn in the opposing lane and then cross back over after the turn.
- Right-turn lanes (sometimes gated).

**Research on Operational Performance**

As part of NCHRP Project 3-65, Johnson and Flannery (*4*) explored the relationship between operating speed and various geometric elements at high-speed, single-lane, rural roundabouts. They collected speed data on 33 approaches of 11 roundabouts in Colorado, Maryland, Maine, and Washington. The study team collected speed data from free-flow vehicles at four locations on each roundabout approach, as shown in Figure 4. They found influences on operating speed from the following factors and developed models to estimate mean and 85th percentile speeds based on those factors. The factors listed in bold are those that were used in the models:

- Approach speeds: **approach width**, effective flare length, and **posted speed limit**.
- Entry speeds: **inscribed circle diameter**, width of truck apron, central island diameter, **effective flare length**, and entry width.
- Circulating speeds: **width of truck apron**, central island diameter, and effective flare length.
- Exiting speeds: inscribed circle diameter, presence of truck apron, central island diameter, approach width, entry angle, entry width, **circulating lane width**, and **exiting lane width**.

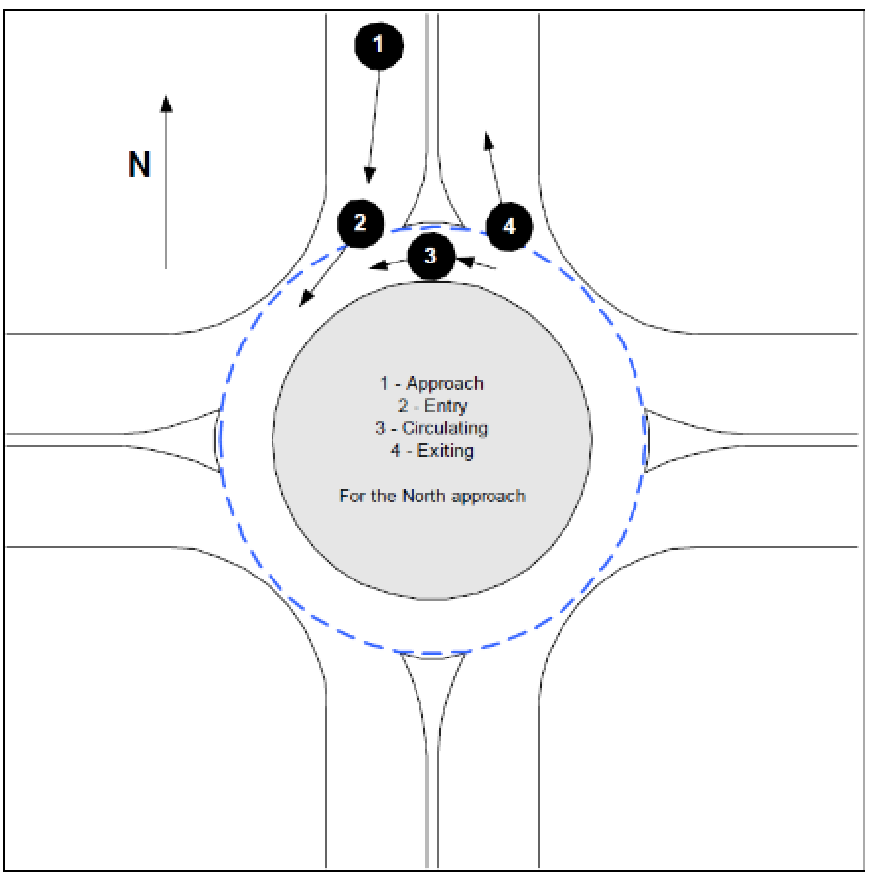



**Figure 4. Spot Speed Data Collection Locations (from Figure 2 in *4*).**

Brewer, Lindheimer, and Chrysler (*5*) reviewed best practices and research literature on speed-reduction techniques for high-speed approaches for all intersection types, as well as treatments for work zones and horizontal curves, to identify treatments with the potential for effectiveness on high-speed approaches to roundabouts. While appropriate deceleration on approaches to roundabouts is primarily accomplished through the use of applicable geometric design principles, the study looked at traffic control device treatments (e.g., traditional signs with and without beacons, pavement markings, illumination, speed-activated signs, and transition zones) to develop a resource for engineers to identify and select appropriate speed-reduction treatments. Information on the effectiveness of these treatments, as well as the potential costs of installation and maintenance, was provided for the practitioner to determine which treatment(s) would be best for the site under consideration. Guidance was also provided for the methodology of conducting a speed study to determine the speed characteristics of a site as well as links to resources for additional information. The project identifies a number of research needs, some specific to particular treatments as well as a general need for field research of the recommended countermeasures on approaches to high-speed rural roundabouts for those treatments not studied previously.

The Brewer report summarizes findings from an FHWA study by Boodlal et al. (*6*) that investigated factors influencing operating speeds and safety on rural and suburban roads. The FHWA study conducted field evaluations of high-friction surface treatments on rural two-lane horizontal curves, optical speed bars or transverse markings on rural and suburban roads, and lane and shoulder reduction on rural two-lane highways. The studies found inconsistent or inconclusive results in effects on speed reduction, though there were some differences in how treatments were applied or evaluated at different locations.

A 2006 study conducted by Chrysler and Schrock (*7*) evaluated various word and symbol pavement markings for speed reduction in advance of horizontal curves in urban and rural locations. The study found that the text CURVE AHEAD sign did not result in speed reduction, but a pavement message consisting of the word CURVE and an advisory speed did result in a 12-mph speed reduction compared to an 8-mph reduction with a warning sign alone in rural areas (Figure 5). On urban curves, a curve arrow and advisory speed was evaluated (Figure 6) and resulted in a smaller percentage of vehicles exceeding the speed limit day and night for both trucks and cars (Table 1).


**Figure 5. Text and Advisory Speed Horizontal Signing Applications (*7*).**

**Figure 6. Urban Freeway Curve Warning Pavement Markings (*7*).**

**Table 1. Percent of Vehicles Exceeding the Posted Speed Limit (*7*).**

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

In a study on the performance of transition zones between high-speed and low-speed roadway sections, Gilmore et al. (*8*) analyzed speed data for sites with roundabouts, sites with transverse pavement markings (TPMs), and sites with no additional treatment. They found that roundabouts and TPMs did not necessarily decrease mean speeds from upstream to downstream of the transition zone, but they did increase speed limit compliance when compared with nontreatment sites. They also found that the rate of vehicles in compliance with the speed limit increased by 15 percent for roundabout sites and 20 percent for TPM sites compared to no additional treatment, and roundabouts sites had an 11 percent higher rate of compliance of vehicles traveling no more than 5 mph above speed limit, as compared with no treatment.

### Research on Safety Performance

Ritchie (*9*, *10*) conducted a study to identify potential issues associated with placing a roundabout on roadways with speed limits of 45 mph or greater. The report looked at five case studies of roundabouts with high-speed approaches in North America. The study documented design treatments for roundabouts with high-speed approaches, and it recommended non-geometric design measures. For design treatments the report concluded that there was very little data to correlate geometric design and safety performance; however, the case studies had common elements that showed early signs of positive performance. These elements were:

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

When accounting for the elements observed at the case studies and the design treatments used around the world, the Ritchie study recommended the following:

- Provide only minimum stopping sight distance at the entry point based on approach operating speed and on observations that excessive sight distance may encourage approaching drivers to maintain high entry speeds.
- Make the central island conspicuous with landscaping and sight-blocking amenities; drivers unfamiliar with the roundabout need sufficient visual information to encourage a change in speed and path.
- Extend splitter islands upstream from the yield line to the point drivers should begin to decelerate (minimum of 200 ft), and use landscaping on the extended island and on the roadside.

- Provide illumination on the transition to the roundabout, and use signs and markings to advise drivers of the appropriate speed.
- Use landscaping on extended splitter islands and roadside to create a tunnel effect for approaching vehicles.

In addition to the above recommendations, the Ritchie study also urged designers to provide sufficient deflection in the design of the approaches to induce speed reduction before vehicles reach the yield line. The authors concluded that entry path radii should be less than 230 feet for best results in single-lane roundabouts and less than 330 feet for multilane roundabout designs. They also concluded, based on the empirical data reviewed in the study, that when flaring roundabout entries, safety impacts of wider entries can be mitigated by decreasing entry path curve values down to 100 feet.

Arndt and Troutbeck (*11*) studied data on geometry, traffic volumes, and crash history at 100 roundabouts in Queensland, Australia, to identify relationships among those factors. They developed models to quantify those relationships for single-vehicle crashes, approaching rear-end crashes, and entering/circulating vehicle crashes. Summaries of those models follow:

- The single-vehicle crash model included traffic flow, length of driver path on the geometric element (i.e., curve), 85th percentile speed on the previous geometric element, and radius of curve. The authors emphasized that this model demonstrated the importance of limiting the difference between the expected operating speeds through successive geometric elements with a recommended limit of 20 km/h (12.4 mph).
- The approaching rear-end crash model included approaching and circulating traffic flow and approach speed. The authors concluded that this model demonstrated the importance of limiting the approach speed to achieve a balance between safety, practical construction, and ease of driver workload; the authors determined a reasonable estimation of the maximum allowable 85th percentile approach speed would be about 60 km/h (37.3 mph). They added that the driver path radius on the approach curve in higher-speed environments would need to be limited to about 60 m (197 ft).
- The entering/circulating crash model included approaching and circulating traffic flow and relative speed between entering and circulating vehicles. The authors stated

> that this model demonstrated the need to minimize the relative speed between entering and circulating vehicles, which could be accomplished by reducing the 85th percentile approach speed (through smaller curve radii and/or smaller entry widths), reducing the 85th percentile circulating speed (through tighter deflection at entry and reducing entry and exit widths), or reducing the angle between approaching and circulating vehicles (through increasing the diameter of the central island, increasing separation between the approach and the succeeding departure leg, or redesigning the approach to be more tangential to the circulating roadway).

As part of their study, Arndt and Troutbeck also provided diagrams of sample dimensions for roundabout designs that corresponded to their models. Those diagrams are reproduced here as Figure 7 and Figure 8; the diagrams are provided in the context of metric units and left-hand drive for Australian conditions.

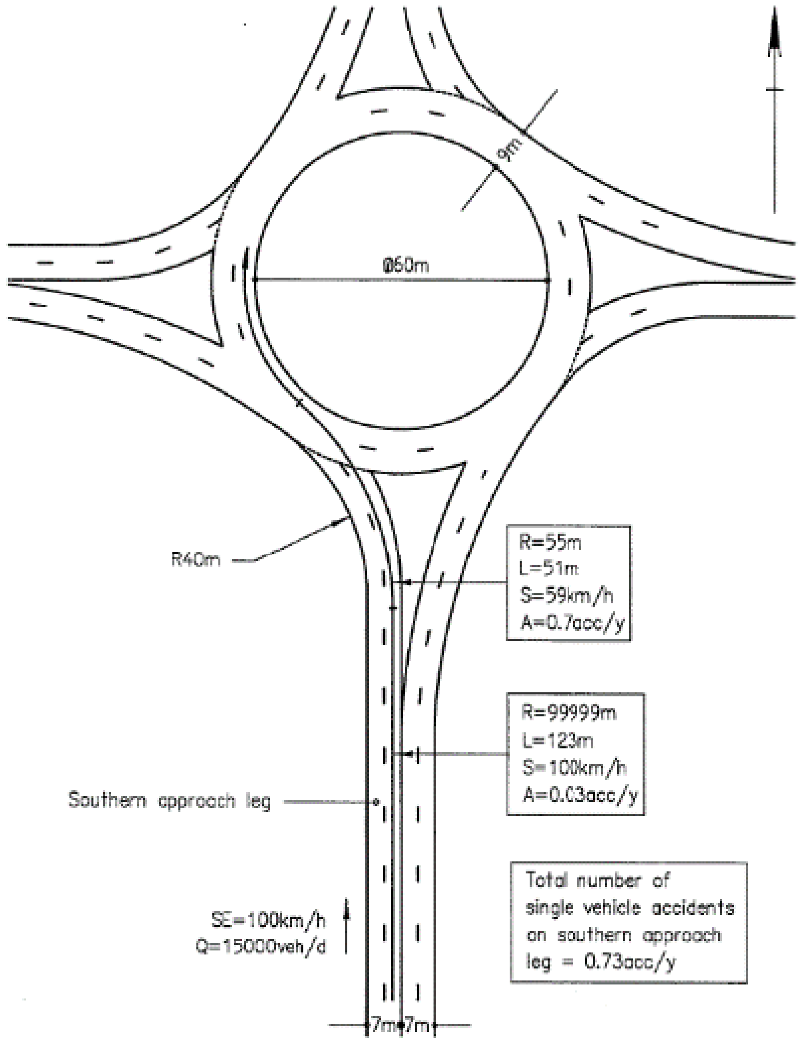



**Figure 7. Typical Rural Roundabout with One Approach Curve (*11*).**

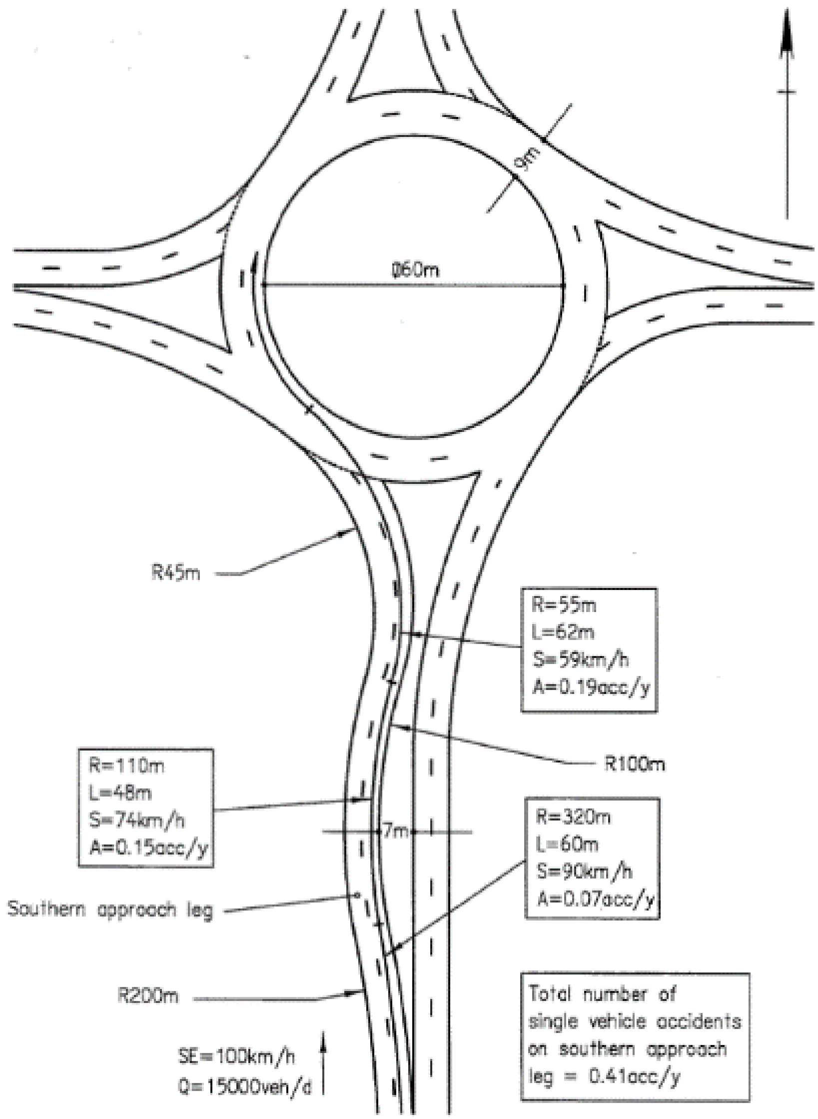



**Figure 8. Typical Rural Roundabout with Three Approach Curves (*11*).**

Isebrands and Hallmark (*12*) conducted a before-and-after crash analysis for 19 rural intersections with high-speed approaches using a negative binomial regression model. Results showed statistically significant reductions (at the 95 percent level) in the total number of crashes (63 percent) and injury crashes (88 percent) after roundabouts were implemented. They also conducted a before-and-after empirical Bayes estimation, which yielded similar results, indicating a 62 to 67 percent reduction in total crashes and an 85 to 87 percent reduction in injury crashes at these rural intersections. Additionally, their results showed that crash types commonly associated with injury, such as the angle crash, were reduced by 91 percent, which was also statistically significant. The authors concluded that their findings validated the hypothesis that roundabouts in a rural environment as well as roundabouts in urban and suburban environments outperformed other intersection safety improvements. Based on their findings, they produced crash prediction models at the planning level for total and injury crashes at rural roundabouts on high-speed roadways to supplement the models produced in the first edition of the American Association of State Highway and Transportation Officials (AASHTO) Highway Safety Manual.

Khattak et al. (*13*) reviewed crash data for four rural high-speed single-lane roundabouts in Kansas that were converted from two-way stop control. They found that total crashes decreased by 58 percent, fatal crashes were eliminated at all locations, non-fatal injury crashes declined by 76 percent, and non-injury crashes were reduced by 35 percent. They concluded that roundabouts constructed on high-speed rural or suburban highways appear to have significant benefits compared to two-way stop-controlled intersections and are recommended for construction with appropriate design, where feasible.

## REVIEW OF EXISTING GUIDANCE

As in any roadway design process, there are trade-offs among certain aspects such as operations, safety, capacity, cost, right-of-way, etc. A design that favors one aspect may negatively affect another one. For example, there are trade-offs in accommodating large trucks on the roundabout approach and entry while maintaining slow design speeds. Increasing the entry width or entry radius to better accommodate a large truck may also increase the speeds of vehicles entering the roundabout. Therefore, designers must balance these competing needs and may need to adjust the initial design parameters. To both accommodate the design vehicle and maintain lower speeds, additional design modifications could be required, such as offsetting the approach alignment to the left or increasing the inscribed circle diameter of the roundabout.

Roundabouts where higher speeds and/or larger vehicles are expected, particularly located in rural or industrial environments, also have design trade-offs. Rural areas typically have higher approach speeds than for urban or local streets, and drivers do not expect to encounter speed interruptions. Industrial or manufacturing areas, and even some freeway interchanges—particularly interchanges with a high proportion of left-turn movements during peak periods and limited queue storage space—tend to carry more large trucks or OSOW vehicles, and thus need to accommodate larger design vehicles. A familiarity with existing design guidance helps a designer better understand all of these issues and potential solutions.

## Manuals and Guidelines from Other Jurisdictions

The project team performed a comprehensive review of publicly available roundabout manuals, design standards, and guidelines to assess the design considerations for roundabouts on high-speed facilities or roundabouts with large trucks or OSOW vehicles. Table 2 shows the guidelines among various departments of transportation (DOTs) and municipalities that were reviewed. Roundabout design aspects related to high-speeds or large trucks/OSOW are discussed in more detail in the following section.

**Table 2. Roundabout Guidelines Reviewed**

| Guideline | High-Speed, Rural Areas | Large Trucks/OSOW |
|---|---|---|
| NCHRP 672 (*1*) | X | X |
| TxDOT (*14*) | X | X |
| Kansas DOT (KDOT) (*15*) | X | X |
| Louisiana DOT (LA DOT) (*16*) | X | X |
| Sugarland, TX (*17*) | X | X |
| Georgia DOT (GDOT) (*18*) | X | X |
| Austroads (*19*, *20*) | X | X |
| Wisconsin DOT (WisDOT) (*21*) | X | X |
| Washington State DOT (WSDOT) (*22*) | X | — |
| Minnesota DOT (MnDOT) (*23*, *24*) | X | X |

*Note: — = not applicable.*

The primary concern in high-speed, rural areas is to make drivers aware of the roundabout with enough time and distance to comfortably decelerate to the appropriate speed (i.e., visibility). Therefore, special design accommodations may be considered to reduce vehicle speeds before entering the roundabout in rural environments. The design of a roundabout in a high-speed environment includes the same techniques of roundabouts in a lower-speed environment but with more emphasis on key principles: retain slow entry speeds, accommodate the design vehicle, and provide visibility.

Many roundabout design guidelines emphasize the principles of using design to control the speed of traffic entering roundabouts in high-speed areas (*8, 9, 10, 23, 19*). The Austroads guide considers 80 km/h (50 mph) as high-speed. It requires the design-controlled vehicle speed within the roundabout to be less than 50 km/h (31 mph) without pedestrians or bikes and less than 30 km/h (19 mph) with pedestrians or bikes (*19*, *20*). The WisDOT roundabout design manual (*21*) relies heavily on NCHRP Reports 572 (*25*) and 672 (*1*) guides but incorporates experiences local to Wisconsin. The Wisconsin guide considers approach speeds ranging from 45 mph to 55 mph as high-speed. The WSDOT roundabout design guide (*22*) considers an approach speed of 45 mph or higher as high-speed. Additionally, the GDOT Design Policy Manual considers speeds greater than or equal to 50 mph as high-speed, and it encourages speed reduction treatments and making drivers aware of the roundabout with sufficient advance warning distance in order to reduce to the appropriate speed to enter the roundabout (*18*). The MnDOT guidance (*23, 24*) does not provide a specific approach speed threshold to define what is considered a high-speed approach for design consideration of roundabouts, but it does contain guidelines for approach geometry (specifically for the development of the approach median and splitter island) for rural and high-speed locations.

*Slow Entry Speeds*

The most important design objective for roundabouts is to maintain low and consistent speeds throughout the roundabout. MnDOT guidance (*24*) specifies that vehicular traffic approaching roundabouts is assumed to decelerate from the selected design speed of the roadway segment to a stop condition at the intersection threshold. Strategies to transition drivers from a high-speed environment on the approach to a low-speed environment at the roundabout entry are discussed below (*15*). Some strategies may have design trade-offs as mentioned earlier.

**Larger Inscribed Circle Diameters (ICD):**

- A roundabout needs an appropriate balance between the need to accommodate the design vehicle, which could be a large truck that needs a larger radius, and the need to keep speeds relatively low. It is recommended that diameters not exceed 200 ft because the larger curves can encourage higher speeds while maneuvering through the roundabout. Crashes that occur at higher speeds are also generally more severe. A larger ICD can reduce the angle between approaching and circulating vehicles, but the size must be appropriate for conditions and not increase the frequency or severity of other types of crashes (*14*).
- A larger-diameter roundabout may have a larger footprint but may be required to accommodate large trucks while providing increased visibility and speed control. However, in some cases, land constraints may limit the ability to accommodate large semi-trailer combinations while achieving adequate deflection for small vehicles. In

such situations, a truck apron may be used to provide additional traversable area around the central island for large semi-trailers. Where provided, truck aprons should be designed with a curbed edge high enough to discourage passenger vehicles from traversing over the top of the apron (*1*).

- The Austroads guide (*19*) suggests the central island radius needs to be at least 14 m (46 ft) and desirably 22 m (72 ft) for single-lane roundabouts. For two-lane roundabouts, the radius should be at least 20 m (66 ft) and desirably 24 m (79 ft).
- WisDOT's guide (*21*) suggests that rural roundabouts may have larger diameters than urban roundabouts. Urban single-lane roundabouts are required to have a minimum inscribed diameter of 120 feet (determined by accommodating a WB-65 vehicle). If the roundabout is located on an OSOW Truck Route, the designer is to verify that the roundabout geometry, splitter islands, and truck apron can accommodate the appropriate OSOW check vehicle. Design of rural multilane roundabouts is similar to urban multilane roundabouts but with higher entry speeds, larger diameters, and recommended supplementary approach treatments.
- MnDOT provides typical ICD ranges from 130 ft to 165 ft for single-lane roundabouts, with a note that the size is mainly dependent on the design vehicle. Thus, the designer is advised that the resulting circulatory roadway width and entry and exit widths, radii, and alignments must work in combination to accommodate the design vehicle and provide the proper amount of deflection and speed control. (*24*).

**Extended Splitter Islands:**

- Splitter islands should generally be extended upstream of the entrance line to the point at which entering drivers are expected to begin decelerating comfortably (*1, 15, 19, 20*). Austroads states that a minimum length of 200 ft is recommended for splitter islands on high-speed approaches (*26*). The length of the splitter island may vary based on the approach speed. The use of flatter and longer tapers in advance of the splitter islands also provides additional visual cues to drivers of a change in roadway environment. The design of the roundabout entry can also provide visual cues to drivers in that the entry curves from the splitter island block the view of the central island as drivers approach the roundabout (*1*).

- At high-speed approaches in Kansas, the raised median portion of splitter islands should extend several hundred feet, with additional channelization provided by curbing or pavement markings (*15*).
- GDOT specifies that splitter islands should be a minimum of 100 feet in length, but they may be reduced to 50 feet on urban roadways with design speeds less than 45 mph (*18*).
- In Minnesota, splitter islands should extend upstream of the yield line 100 to 150 feet on low-speed approaches and 200 to 300 feet on high-speed approaches (*24*). Under some circumstances, longer or shorter islands may be considered, such as to limit or provide access to an adjacent minor road or driveway. On high-speed approaches, designers are instructed to provide a 4-ft minimum (6-ft preferred) wide nose where the median is introduced to allow space for sufficient signing.
- To accommodate heavy vehicles, some road agencies in Australia prefer the prolongation or projection of the splitter island curb to pass through a point in the circulating roadway about 1.5 m (5 ft) from the central island. This is to assist heavy vehicle drivers to ensure that the vehicle tracks on the pavement rather than mounting the island. It also assists drivers in changing their steering from one direction to the other (*19*).
- LA DOT specifies that the splitter islands shall have a minimum length measured along the approach as shown in Table 3 (*16*).

**Table 3. Length of Curbed Splitter Island (adapted from *16*, pg. 6–13).**

| Posted Speed | Minimum Length of Curbed Splitter Island |
|---|---|
| ≤ 35 mph | 50 ft |
| 35 mph < x ≤ 45 mph | 75 ft |
| > 45 mph | 150 ft |

**Approach Alignments:**

- Providing an offset-left approach alignment increases the deflection and allows for slower entry speeds (*1*, *15*). It minimizes entry/circulating collisions while reinforcing the priority of circulating traffic (*24*). It is also beneficial for accommodating large trucks with a small ICD—it allows for larger entry radius while maintaining deflection and speed control. A left offset is preferred for high-speed approaches (*18*). The exit design may require much larger approach radii, ranging from 300 to 800 ft or greater. Larger exit radii may also be desirable in areas with high truck volumes to provide ease of navigation for trucks and reduce the potential for trailers to track over the outside curb (*1*).

- The design of a roundabout approach is independent of the design criteria for the corresponding roadway classification of the approaching roadways. For design purposes, the roundabout intersection design criteria begin 200 ft prior to the intersection for approaching roadways posted 45 mph and below and 400 ft prior to the intersection for approaching roadways posted greater than 45 mph (*16*).
- If two approach legs intersect at an angle substantially less than 90°, then the difficulty for large trucks to successfully navigate the turn is increased. Providing a large corner radius to accommodate trucks may result in a wide portion of circulatory roadway, resulting in increased speeds and possibly reduced safety performance if the additional circulatory roadway width is mistakenly interpreted by drivers to be two lanes (*1*).

**Curbing:**

- According to NCHRP 672, curbs should be provided on all approaches on high-speed facilities to alert drivers of a change in the driving environment. Consideration should also be given to reducing shoulder widths. Curbs help to improve delineation and to prevent corner-cutting, which helps to ensure low speeds. In this way, curbs help guide vehicles to the intended design path. The designer should carefully consider all likely design vehicles, including farm equipment, when setting curb locations (*1*, *15*).
- KDOT specifies standard 6-inch outside curbs. It notes that vertical clearance should be analyzed for design vehicles. The truck apron should have a 3-inch curb with a radius, and the central island should have a 6- or 8-inch curb (*15*).
- GDOT specifies curbing for the outside edge of all roundabouts, including the entry radius, circulating roadway, and exit radius. For rural roads, outside curbing is desired out to the length of the desired deceleration distance (*18*).

- Because roundabouts are intentionally designed to slow traffic, narrow curb-to-curb widths and tight turning radii are typically used. However, if the widths and turning requirements are designed too tight, it can create difficulties for large vehicles. Large trucks and buses often control many of the roundabout's dimensions, particularly for single-lane roundabouts (*1*). More details are provided in the Accommodate Design Vehicle section of this chapter.
- The WisDOT guide (*21*) requires 6-inch vertical face curbs on both sides of the roadway to be incorporated for low-speed approaches. The purpose of the vertical face curbs is to control the fastest speed paths at the roundabout entrances and exits. For OSOW vehicles, a 4-inch mountable curb and gutter may be used in limited situations to better accommodate truck tires that may have to go over the curb or the splitter island.
- Rural high-speed approach design will require a transition section from the undivided rural highway normal segment to the approach of the roundabout where the shoulders will narrow and vertical curb will be introduced (*21*, *22*).

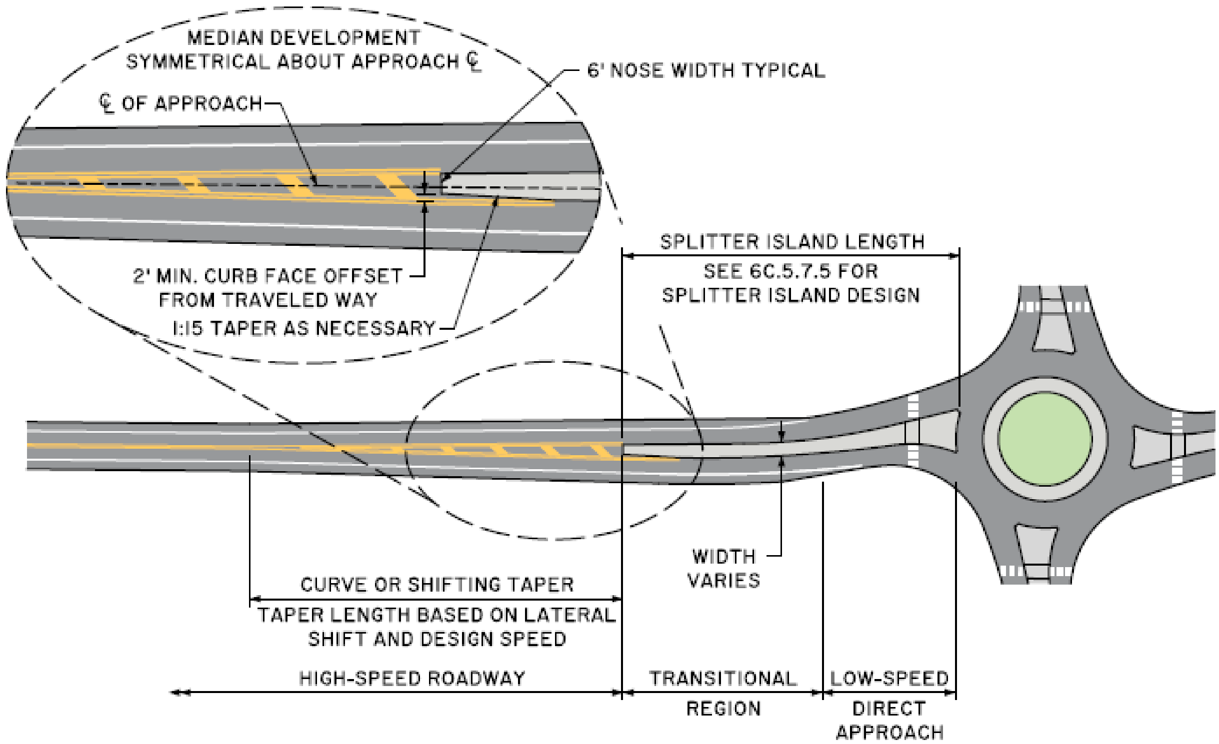
**Approach Curves:**

- Roundabouts on high-speed facilities, even with extra signing efforts, may not be expected by approaching drivers, resulting in erratic behavior and an increase in single-vehicle crashes. All high-speed approaches should include speed reduction treatments, such as horizontal curvature (*18*). The alignments approaching a roundabout are intended to incrementally decrease driving speeds, properly align the driver to the roundabout, and develop the lateral space necessary for robust entry curvature (*24*).
- The radius of an approach curve (and subsequent vehicle speed) has a direct effect on the frequency of crashes at a roundabout. A method to achieve speed reduction that reduces crashes at the roundabout while minimizing single-vehicle crashes is the use of successive curves on approaches (*1*, *15*). NCHRP 672 cites a study in Queensland, Australia, that found that limiting the change in 85th percentile speed on successive geometric elements to approximately 12 mph is related to a reduced crash rate. The use of successive reverse curves in advance of the roundabout

approach curve reduced the single-vehicle crash rate and the sideswipe crash rate on the approach. Thus, it is recommended that approach speeds immediately prior to the entry curves of the roundabout be limited to approximately 35 mph to minimize high-speed rear-end and entering–circulating vehicle crashes (*1*).

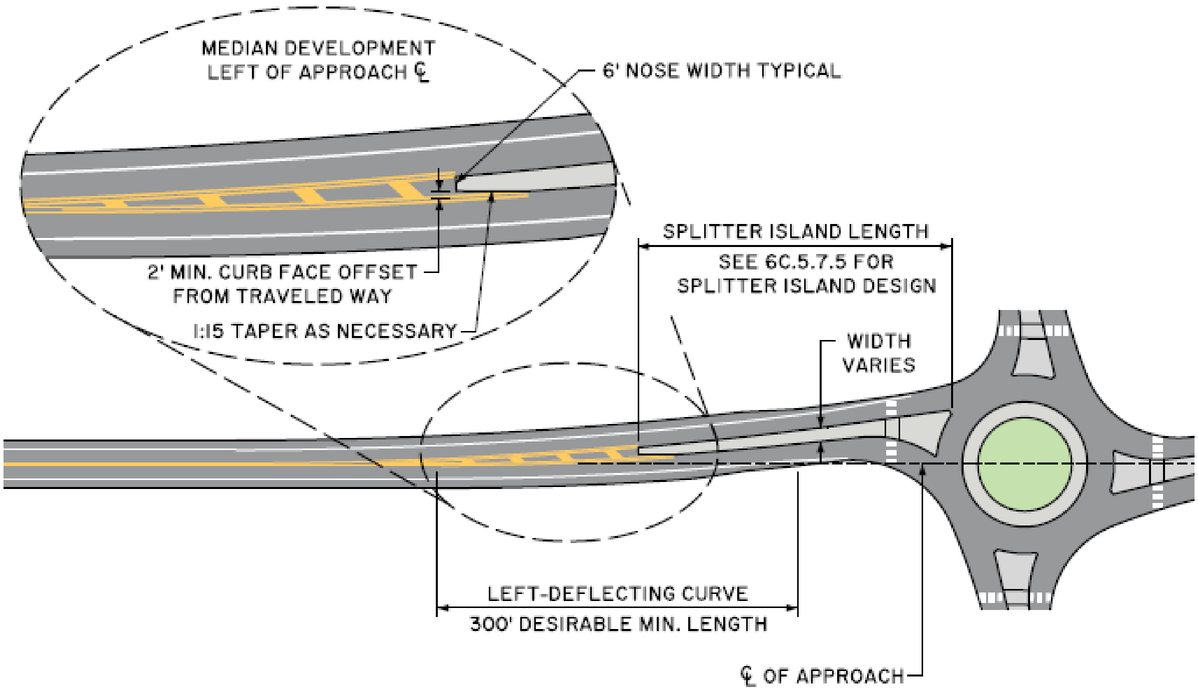
- In particular, the Austroads guides (*19, 20*) suggest that an entry may comprise a single left-hand curve (equivalent to right-hand curve in the United States) on the immediate approach to a roundabout. The suggested maximum entry path radius is 55 m (180 ft) for single-lane entries or two-lane entries for vehicles staying in the correct lanes for all approach speeds. For cutting across lanes on two-lane entries, the maximum path radius is 1.5 times the actual path radius when staying in the correct lane (*19*). Using reverse curves may potentially minimize single-vehicle crashes on road approaches with operating speeds 80 km/h (50 mph) or higher. When the approach speed is 100 km/h (62 mph) or higher, two or three curve reversals may be used to progressively slow drivers. Reverse curves are suggested for downhill approaches with a slope greater than 3 percent. The reverse curves should be designed so that each approach curve and the central island are visible to drivers before they reach the first curve. The maximum speed reduction between successive reverse curves should be less than 20 km/h (12 mph). To accommodate heavy vehicles, Australia roadway agencies have used a short horizontal straight line between the entry curve and the circulating roadway. In this case, a length of 5 m (16 ft) is usually sufficient. Alternatively, providing spirals at the ends of each reverse curve may also achieve a satisfactory result.
- WSDOT suggests chicanes be considered when posted speeds near the roundabout are 45 mph or higher. Chicane curves are designed with successively smaller radii to successively reduce vehicle speeds approaching the roundabout entry (*22*).
- MnDOT (*24*) provides illustrations of two standard geometric design methods for high-speed approaches, reproduced here as Figure 9 and Figure 10. Their guidance states that the designer's choice between these or other geometric designs will typically depend on space availability, geometric and site specifics, design speed of the approach roadway, and designer preference and judgment. The designer is also advised that the development lengths and construction limits for the two illustrated

methods are generally equal or comparable, but the designer should exercise flexibility in developing a site-specific design that best fits the needs of a given location.




Design speed tapers in both directions split and channelize the traveled ways (curves may be used to smooth the deflections). Dual alignments tie into the tapered paths and carry forward into the roundabout. This method is distinguished by its symmetry, which is well suited to narrow rights of way or where grading needs to be balanced.

**Figure 9. Symmetrical Median Development for High-Speed Approach to Roundabout in Minnesota (reproduced from Exhibit 6E-23a in *24*).**




Smooth alignments simplify the path for the incoming direction of travel: a left-deflecting transition curve and right-deflecting entry curve. The splitter island is developed entirely to the left of the approach centerline, minimizing the potential for vehicular impacts on the island nose. Widening and grading are asymmetrical toward the exit roadway.

**Figure 10. Median Development Left of Approach Centerline for High-Speed Approach to Roundabout in Minnesota (reproduced from Exhibit 6E-23b in *24*).**

*Accommodate Design Vehicle*

The location of the roundabout may govern the specific design vehicle selected. Recreational routes are often frequented by motor homes and other recreational vehicles. Agricultural areas are frequented by tractors, combines, and other farm machinery. Manufacturing areas may see oversize trucks. Each of these special design vehicles should be incorporated early in the design process since they can affect the fundamental design decisions of size, position, and alignment of approaches (*1*). For example, the size of the ICD is largely dependent on the design vehicle, and accommodating large trucks may increase the entry and circulatory speeds of cars.

The selection of the design vehicle should be sensitive to the context of the roadway network and adjacent development (*1*, *14*, *17*). For example, a typical design vehicle for rural roadways is WB-67 for the circulatory roadway and a bus for the truck apron (*17*). However, the ultimate design vehicle will be selected during the pre-design meeting. The roundabout should be designed such that the design vehicle can navigate it with a 1-ft clearance from the turning radius to any non-mountable curb face. The front wheels of the design vehicle should not encroach on the truck apron. LA DOT and GDOT also require roundabouts to use a WB-67 as the design vehicle (*16*, *18*). Additionally, LA DOT requires a single-lane roundabout to have a 110-ft minimum diameter. Multilane roundabouts must have a 175-ft minimum diameter, which allows the design vehicle to encroach into the adjacent lane but still maintain an 11-ft minimum clear width. GDOT also requires that buses be accommodated in urban areas and single-unit trucks be accommodated in rural areas, both without tracking over the truck apron (*18*).

The WisDOT guide (*21*) has extensive information on design considerations of OSOW trucks. WisDOT uses the WB-65, the largest vehicle allowed on their state highway system without a permit, as the design vehicle for roundabouts. WisDOT has maps of OSOW Truck Routes. If the roundabout is located on such a route, the WisDOT OSOW vehicle inventory should be checked to determine the design vehicles. Additionally, intersections of two state trunk highways and state highways that make an abrupt turn at an intersection should accommodate these check vehicles: the WB-92 (formerly WB-67 Long), farm combine, and 80-ft mobile home transport vehicles. If the existing intersection geometrics did not accommodate a multiple-trip permitted vehicle by staying within the curb face, improvements need to be proposed and completed.

Minnesota guidance (*24*) references a joint study with WisDOT to investigate the needs of large combination vehicles and their effects on roundabout design. In conjunction with that study, they established three design cases to classify multilane roundabouts:

- Case 1: These are designed so that combination trucks encroach into adjacent lanes while entering, circulating, and exiting the roundabout.
- Case 2: Trucks do not encroach into adjacent lanes on entry—utilizing a gore area of vane striping—but may encroach into adjacent lanes while circulating and exiting.
- Case 3: Sufficient lateral space is provided using combinations of vane striping and truck apron so that trucks can maintain lane discipline throughout while entering, circulating, and exiting.

Observation (*24*) suggested that truck drivers on Case 1 roundabouts were adept at occupying both lanes to avoid conflicts. At Case 2 and Case 3 roundabouts, drivers typically kept their lane on approach (91 percent) and while circulating (83 percent) when potentially conflicting traffic was present, but they were less diligent with lane-keeping on approach (71 percent) and circulating (37 percent) when such traffic was not present. They also found that truck drivers typically avoided using the truck apron regardless of entry design. The study observations suggested that providing Case 2 or Case 3 accommodation was beneficial to trucks and generally utilized as intended, while Case 1 design can be considered adequate but entails added delay and driving complication for truck drivers. As a result, MnDOT practice is to provide Case 2 designs at multilane roundabouts, and it does not allow Case 3 designs because their size and pavement area make them undesirable based on expected vehicle speeds, construction cost, and maintenance liability. Case 1 design is not preferred in Minnesota but may be acceptable in certain circumstances where entry widths may be constrained and/or truck volumes are less than 5 percent of average daily traffic (ADT).

An illustration of a Case 2 design from the MnDOT guide is provided in Figure 11. The path of the combination truck may encroach into the adjacent circulatory lane once the truck enters the roundabout. Under these circumstances, passenger vehicles were generally observed to stay behind trucks and not attempt to circulate alongside them, but the truck driver must exercise care to avoid conflicts.

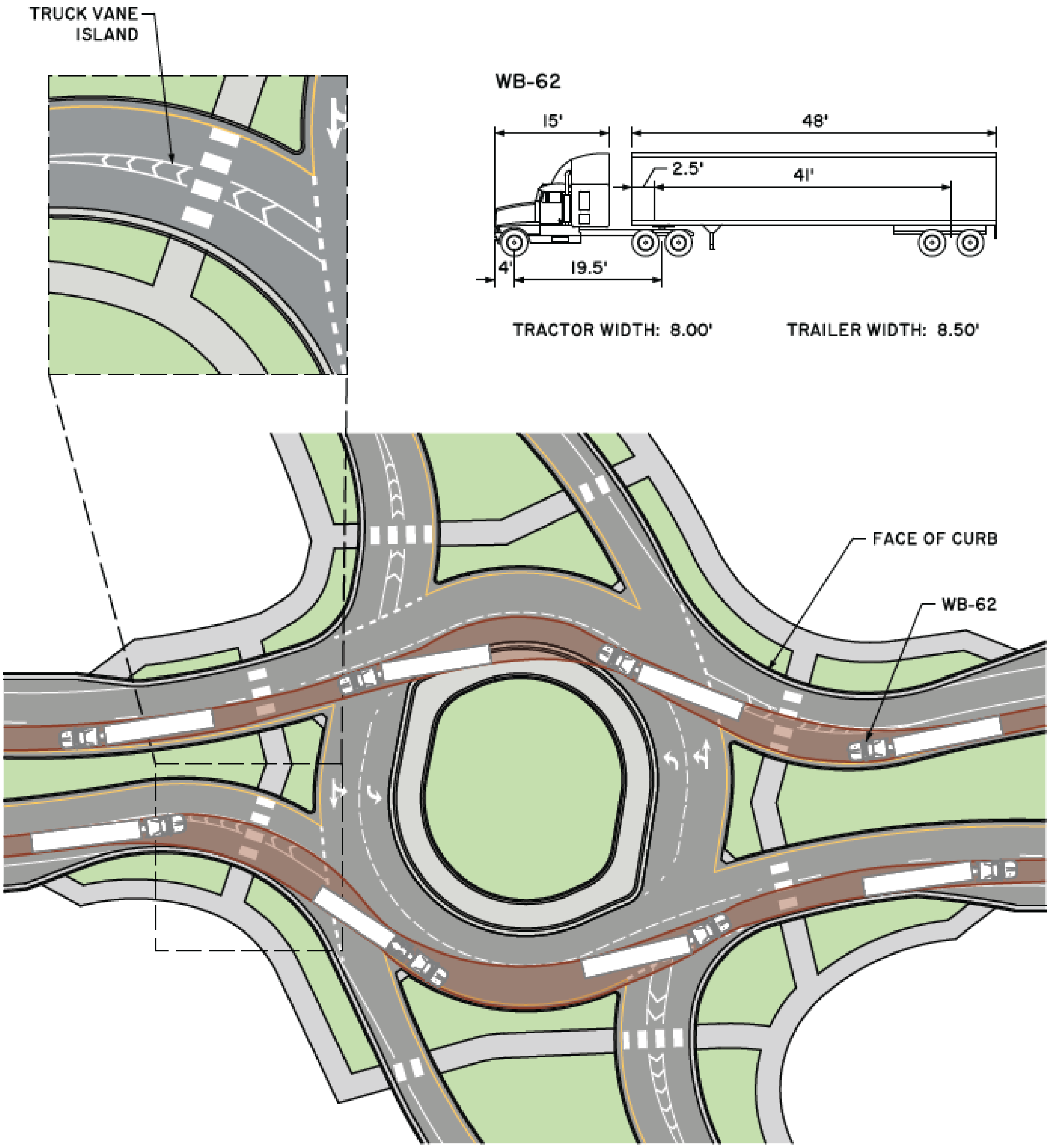



**Figure 11. Multi-lane Roundabout Entry Design (No Entry Path Overlap) in Minnesota (reproduced from Exhibit 6E-24 in *24*).**

The KDOT guide states that "the roundabout should be designed to accommodate the largest vehicle reasonably anticipated to use the intersection." The design vehicle is selected from three general categories: large vehicles without trailers, which generally do not use the truck aprons; large vehicles with trailers, which generally allow the vehicles' rear trailer to use the truck apron; and OSOW vehicles, which generally require special accommodations beyond a truck apron. OSOW are vehicles that typically require special permits due to their extreme weight and size and are also sometimes referred to as “superloads” (*1*).

The primary concerns for OSOW vehicles are the length, width, low ground clearance, and swept path of the vehicle body and tires as well as the load. However, the designer needs to balance the OSOW vehicles’ needs with the basic design principles of controlling fastest path speeds and path alignment (*15*). Besides the typical strategies for accommodating larger vehicles (some discussed earlier such as larger ICD, wider approach widths, wider circulatory roadway, and larger radii), the KDOT guide also discusses additional possible strategies grouped by four different treatment types (not all are endorsed by KDOT):

- Bypass treatments such as:
  - Providing a bypass so OSOW vehicles can avoid the roundabout altogether.
  - Designing a temporary shoofly bypass to remain as a permanent feature for OSOW vehicles.
  - Allowing OSOW vehicles to make a left-turn in advance of the roundabout, such as the one shown in Figure 12, where they are projected to make left-turns regularly.
  - Providing a central island cut-through bypass where OSOW vehicles are projected to make through movements regularly. Removeable or foldable traffic signs, landscaping, or some other visual element should be used to block the cut-through when not in use. One example from the KDOT guide is found in Figure 13.
- Traffic control device treatments such as designing signs and sign supports to be easily moved and put back into place.
- Central island treatments such as increasing the truck apron’s width. It should be verified that drivers can still see the central island as they approach the roundabout and that proper deflection and speed control are maintained. A different material or pattern should also be used for the apron’s surface from that used for the sidewalk so that pedestrians do not perceive the apron as a sidewalk.
- Approach treatments such as an outside truck apron and/or a mountable splitter island may be considered when other design modifications are unavailable. Figure

14 shows a striped outside truck apron for the swept path of entering OSOW vehicles. It should be verified that proper deflection and speed control are maintained. The impact on pedestrian/bicyclist facilities and vehicle vertical clearances should also be assessed.

Design consideration for OSOW trucks can be made through the width of circulating roadways, entry and exit approaches, and exit curves for different design vehicles, truck aprons, and splitter islands (*19*, *21*).

Bing Maps. Image courtesy of Simmons ©2013 Microsoft Corporation

**Figure 12. Advanced Left-Turn Movement at the Intersection of Goudsestraatweg (N459)/A12 in Reeuwijk-Brug, Netherlands (reproduced from Exhibit 6-39 in *15*).**

Courtesy of Steven Diebol

**Figure 13. United Kingdom Roundabout with OSOW Truck Accommodation through the Central Island. (Mirrored Image) (reproduced from Exhibit 6-41 in *15*).**


**Figure 14. Striped Outside Truck Apron at the Intersection of I-70/S East Street/E Chestnut Street/E Ash Street in Junction City, Kansas (reproduced from Exhibit 6-48 in *15*).**

*Proper Width of Circulating Roadways*

The Austroads guide (*19*) provides different widths of the circulating roadway for different design vehicles under different radii of the central island. The width decreases as the radius of the central island increases. For example, to accommodate a 19-m (62-ft) semi-trailer, the single-lane circulating roadway should have a width of 7.2 m (24 ft) for a central island of 14 m (46 ft), which is the minimum radius for an approach speed of 50 mph. The width drops to 4.8 m (16 ft) when the central island radius is 60 m (197 ft) or larger.

In Wisconsin, if an existing roundabout design cannot accommodate a right turn movement for a particular design vehicle without encroachment, the designer will have to balance the entry throat width, circulating roadway width, and the possible need for a small truck apron behind the outside curb for off-tracking. It is generally a safer design to keep the roundabout entry lane throat width on the narrow side, usually less than 22 feet (*21*).

The MnDOT Facility Design Guide (*24*) states that the curb-to-curb width of a single-lane roundabout is typically 20 to 24 ft, with 22 ft being most common. For multilane roundabouts, the width tends to be 100 to 120 percent of the maximum entry width, with lane widths between 14 and 16 ft. Cross-slope may range from 1.5 to 2.0 percent sloping to the outside (i.e., the driver's right); MnDOT typically does not crown their circulatory roadways to simplify construction and to eliminate the need to drive across a crown line when entering and exiting the roundabout.

*Proper Width of Entry and Exit Roadways*

There are cases in which the use of adequate entry lane widths for large vehicles will lead to inadequate entry curvature. In these cases, it is preferable to reduce the entry lane widths to provide adequate curvature and provide encroachment areas to cater for the movement of larger vehicles. The Austroads guide (*19*) also provides an option of adding an auxiliary lane with tapers at the entry for deceleration and at the exit for acceleration to accommodate high left-turn (equivalent to right-turn in the United States) demand. In this case, the selection of the entry and exit widths needs to consider the auxiliary lane properly.

Guidance in Minnesota indicates that single-lane entry widths of 19 to 22 feet are commonly needed to accommodate control vehicles depending on the turning radius and angle (*24*).

*Exit Curves*

After having been slowed down by the entry curve(s) and circulating on a roundabout, drivers should be able to accelerate from the circulating roadway through the exit. Therefore, the exit should either be tangential to the central island or be designed with a relatively large radius. This limits the amount of side friction drivers use at this location and minimizes the single-vehicle crash rate on the exit curve. If using short horizontal straights between circulating carriageway and exit curves, a length of 5 m is usually sufficient to accommodate heavy vehicle dynamics (*19*).

Minnesota guidance states that designs may vary depending in part on the orientation of the exit legs, but for single-lane roundabouts the exit path is either a curve beginning within the circulatory roadway—typically with a radius greater than 300 feet—or a tangent emanating from the circulatory roadway alignment (*24*).

*Truck Aprons*

WisDOT requires the truck apron width to be a minimum of 12 ft for both single-lane and multilane roundabouts. A 12-inch thickness is desired for the truck apron. The truck apron should be reddish-colored concrete. The slope of the pad should be a maximum of 1 percent. It is becoming common to widen the truck apron along the sides to accommodate OSOW vehicle through movements. Additional pavement (behind a mountable curb) may also be provided along the right side of the entries to accommodate wheel off-tracking. If the roundabout is on an OSOW Truck Route, designers conduct a vehicle horizontal turning check and a low vertical clearance check with the OSOW vehicle inventory. If clearance issues are found, reconfigure the slopes within the conflict areas and check the surrounding area (i.e., approaches) for additional conflict points. Truck aprons should be sloped 1 percent toward the roadway on all roundabouts. Consider a pill-shaped central island or other shape where appropriate to accommodate the anticipated OSOW turning maneuver (*21*).

MnDOT says the truck apron should normally be 13 to 14 feet wide to allow for efficient snow removal. Variations to this width and circular shape are acceptable when necessary to accommodate control vehicles. Paving the truck apron with a contrasting material, color, or surface treatment compared to the circulatory roadway can further delineate it from the circulatory roadway and help clarify to drivers that it is not meant for common use. Paving the apron with a different material or color than used for the sidepath system can help discourage pedestrians from crossing to the central island. This contrast can be achieved by using concrete for the apron and asphalt for the circulatory roadway or by using a colored concrete mix, although colored mixes have been associated with reduced durability and service life (*24*).

On multilane roundabouts with Case 2 design in Minnesota, large vehicles can use the entire width of the circulatory roadway to negotiate through the roundabout. In most cases, however, the standard design vehicle should stay in lane for all turning movements while using the truck apron when on the inside lane. In some extreme cases, roundabouts have been designed with a gated roadway through the center island to accommodate oversized or emergency vehicles (*23*).

### *Splitter Island*

WisDOT (*22*) requires that the reddish-colored concrete pad, without stamping, should be installed in the splitter islands where OSOW vehicles may drive to negotiate the roundabout.

### *Visibility*

A critical feature affecting safety at rural intersections is the visibility of the intersection. Roundabouts are similar to stop-controlled or signalized intersections in rural or high-speed environments except for the presence of curbing along roadways that are typically not curbed. Single-vehicle crashes can be minimized with enhanced visibility of the roundabout and its approaches. The geometric alignment of approach roadways should be constructed to maximize the visibility of the central island and the shape of the roundabout whenever possible. Where sufficient visibility cannot be provided through geometric alignment then additional treatments such as signing, pavement markings, or advance warning beacons should be considered similar to those that would be applied to rural stop-controlled or signalized intersections (*1*).

### *Landscaping*

The GDOT *Design Policy Manual* recommends that landscaping be installed in most roundabouts. Landscaping in the central island can provide a visual identity of the roundabout location to drivers approaching from a distance. This landscaping of the central island can block the sight lines of the approaching driver so that the driver only sees the island and not the roadway past the roundabout (*18*). The GDOT manual also requires landscaping when a roundabout has one or more high-speed approaches (i.e., speeds greater than or equal to 50 mph).

The MnDOT Facility Design Guide expresses similar support, noting that appropriate landscaping in the center island, splitter islands, and approaches can improve both visual quality and safety, making the intersection and its components more conspicuous to drivers and visually reinforcing the geometry while maintaining adequate sight distance (*24*).

### *Sight Distance*

Roundabouts must be designed to provide the same approach sight distance as other intersections (*19*). The Austroads guide mandates the approach alignment to provide a good view of the splitter island, the central island, and, preferably, the circulating carriageway. The alignment must also provide adequate sight distance for drivers to detect an acceptable gap of 4 to 5 sec for detecting potential conflicting movements with vehicles entering from the approach immediately to the left and vehicles traveling in the circulating lanes. Designers can choose to check the sight triangle for a driver to detect potential conflicts long before reaching the roundabout approach. The above requirements for sight distance are based on passenger vehicles; for roundabouts with a high volume of large or special trucks, the stopping sight distance for trucks should also be provided.

Minnesota guidance also describes sight distance requirements similar to those for non-roundabout intersections, with four specific sight distance categories described as follows:

- Approach sight distance: Stopping sight distance (SSD) is provided at all points along the road in roadway design. Specific to roundabout intersections, the raised island, entry curvature, crosswalk, and yield line should be within the line of sight of all approaching drivers. SSD to the crosswalk is the controlling element for approach sight distance.
- Entry sight distance: Intersection sight distance (ISD) is provided for approaching drivers to decide whether they need to stop at the yield line or continue into the roundabout. This is analogous to the approach sight triangle condition of ISD Case C for conventional intersections in AASHTO's *A Policy on Geometric Design of Highways and Streets* (commonly known as the Green Book) (*27*). This sight distance is based on a 5-second headway distance and an assumed entry speed of 20 mph.
- Circulating sight distance: SSD is provided for drivers within the circulatory roadway. This sight distance is achieved through the use of truck aprons and central island landscaping design and is rarely a controlling factor.
- Sight distance to the downstream crosswalk: SSD to the downstream crosswalk is necessary for appropriate driver yielding behavior at the crosswalk. Sight-corner restrictions may be present in acute angles of skewed intersections or due to buildings in urban settings.

*Speed Reduction Countermeasures*

While speed reduction should be achieved through appropriate design of the roundabout approach, sites where drivers approach at excessive speeds may necessitate the use of speed reduction treatments. A number of potential treatments are discussed in the previous section titled Research on Operational Performance.

# CHAPTER 3: EXISTING GUIDANCE FOR INNOVATIVE INTERSECTIONS

This chapter summarizes the findings from a review of existing guidance materials. The review of existing guidance included a traditional literature review, which revealed limited comprehensive research on the topic due to these intersection types being relatively new. State documents were identified that had policies and guidance material with respect to innovative intersections. The FHWA website has links to several reports and videos, and these are included in this chapter.

Various names are used for the intersections that manage left-turn movements in a manner that is different from conventional intersections. Innovative intersection is the term used within this project; however, this category of intersections is also known as alternative intersections or unconventional intersections.

## OVERVIEW OF INNOVATIVE INTERSECTIONS

### Safety Benefits

Innovative intersections use a variety of techniques for accommodating left-turn maneuvers. Regardless of the technique, indirect left-turns provide a reduction in the number of conflict points when compared to a conventional intersection. Traditionally, safety performance has been linked to the number and type of conflict points. In this approach, it is assumed that fewer conflict points will result in fewer crashes. By reducing the number of available vehicle conflicts, road users who violate traffic control will still be exposed to fewer intersection conflicts than at conventional intersection locations. This reduction in conflict points is expected to translate into safety benefits. Because of the limited number of installations, the safety research on the topic is sparse.

### Capacity Benefits

An innovative intersection, as a result of having fewer signal phases per cycle, provides more green time to each of its phases than conventional intersections with four, six, or eight signal phases per cycle. It has been well documented that with a decrease in the number of signal phases per cycle there is a corresponding increase in the lane capacity of the intersection. Since each lane in an innovative intersection can move more vehicles than its conventional intersection counterpart, fewer through lanes and/or turning lanes are required to store and move the same volume of traffic. This streamlined cross-section results in less right-of-way to construct the lanes and less cost to build them. As a result of reduced delay, vehicle emissions generated from idling motor vehicles will also be minimized. Finally, reduced signal phases will decrease the frequency of starts and stops associated with multi-phase conventional intersections.

### Highway Capacity Manual, 6th Edition

Recently, information on the capacity of alternative intersections has garnered inclusion in the most recent edition of the *Highway Capacity Manual* (HCM) (*28*) in Chapter 23, which is dedicated to ramp terminals and alternative intersections.

## TYPES OF INNOVATIVE INTERSECTIONS

There are several types of intersections that fall under the umbrella of innovative intersections. FHWA has grouped these intersection types into the following three categories:

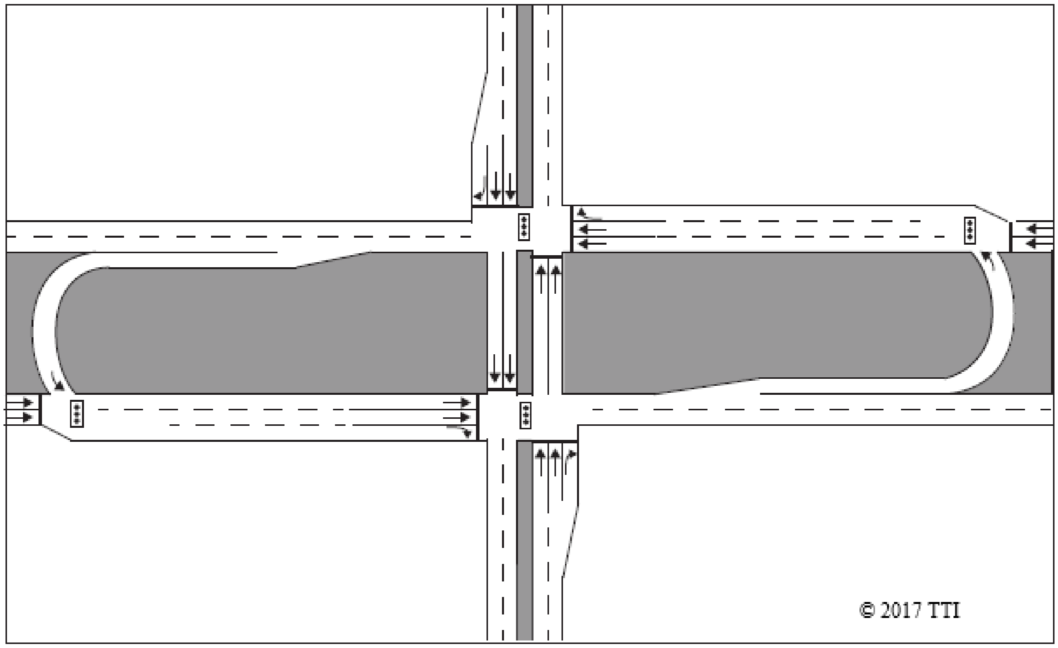
- U-turn-based (*29*).
- Crossover-based (*30*).
- Other (*31*).

U-turn-based intersections include median U-turns (MUTs) (*32*) and restricted crossing U-turns (RCUTs); crossover-based intersections include the displaced left turn (DLT) and the diverging diamond interchange (DDI); while the Other category includes the quadrant roadway (QR), jughandle, continuous green T (CGT), offset T, and single point urban interchange (SPUI). The characteristics of the aforementioned intersections, as well as several others, were discussed in detail in a 2010 FHWA informational report titled *Alternative Intersections/Interchanges: Informational Report* (AIIR) (*33*). The report also included discussion of the double crossover diamond and DLT interchanges. The most common alternative intersection designs are discussed within the remainder of this chapter.

### U-Turn-Based Intersections

#### *Median U-Turns*

MUTs, sometimes referred to as Michigan Lefts, prohibit left turns by both the major and minor roads. Drivers wanting to turn left from the minor road initially turn right at the intersection before passing through a U-turn lane and then traveling towards their destination. A sketch of a typical MUT configuration is shown in Figure 15. Key reference documents for MUTs include the FHWA's *Median U-Turn Intersection Informational Guide* (*32*).

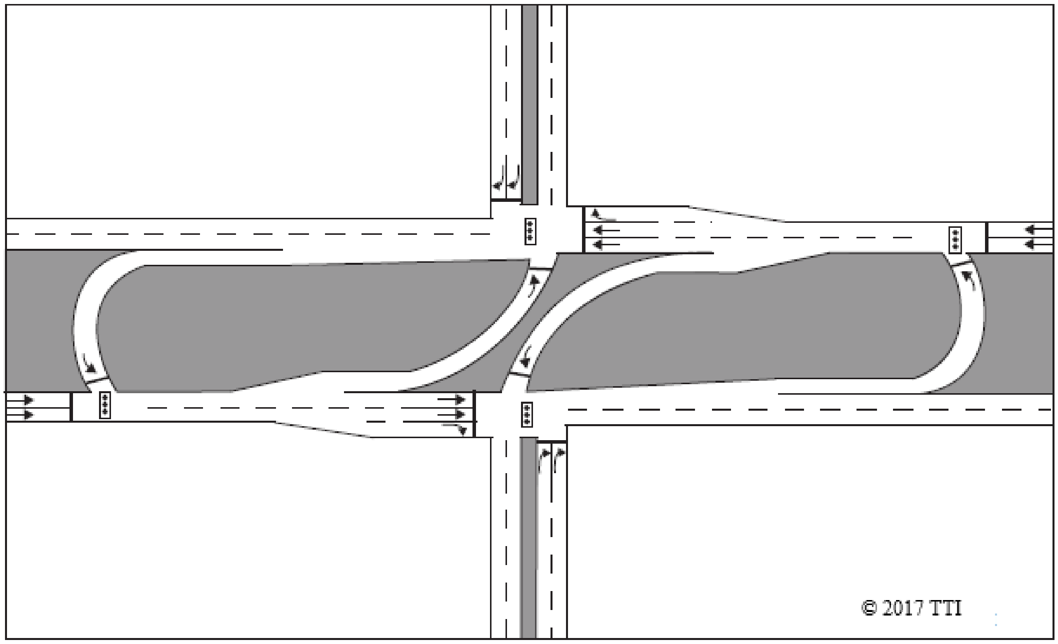



Source: Chrysler et al. (*34*).

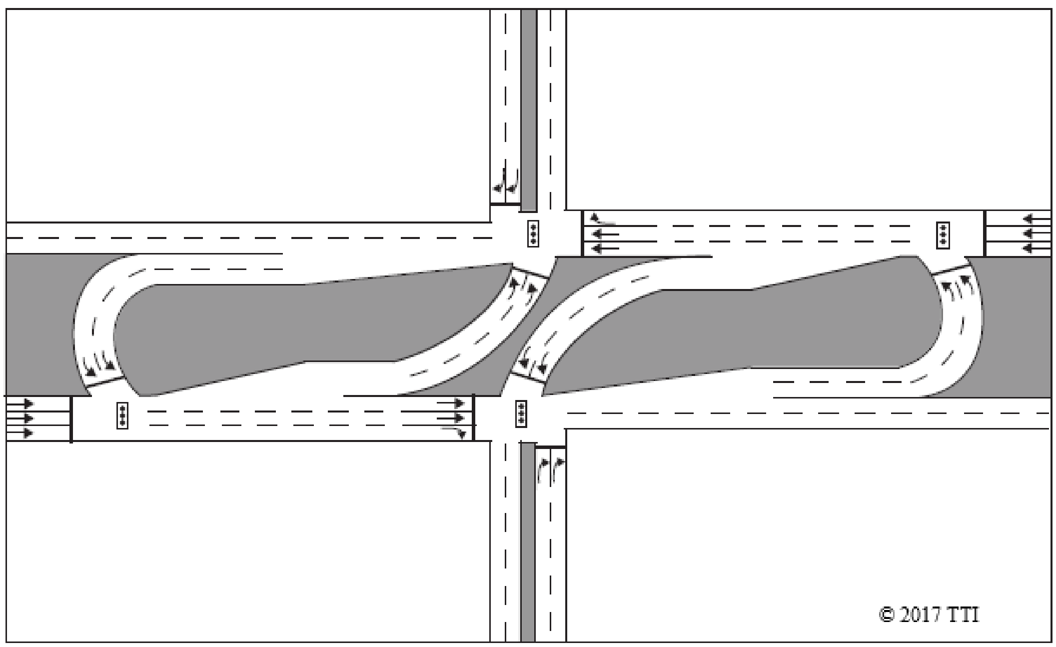
**Figure 15. Typical MUT Configuration with Through Movement Allowed from Minor and with Signalized U-Turns.**

*Restricted Crossing U-Turns*

A series of RCUT intersections are often referred to as a superstreet when used as the primary intersection along a corridor. RCUTs function similarly to MUTs with two exceptions. First, major street traffic can turn left at the intersection. Second, minor street through movements are prohibited. Minor street through traffic uses the U-turn in the same fashion as left-turning vehicles, but then turns right to resume their initial course. Figure 16 and Figure 17 illustrate typical RCUT designs. Additional information regarding this treatment is available in a 2014 report by Hummer et al. (*35*).



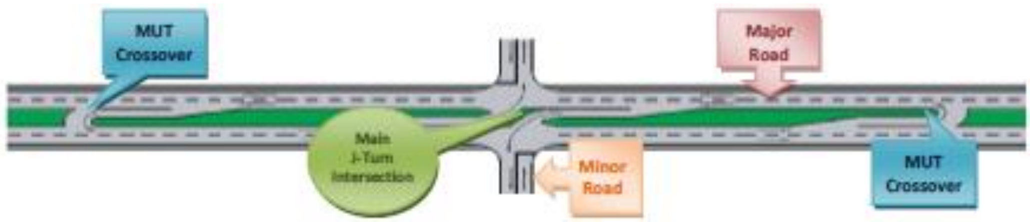

Source: Chrysler et al. (34).
**Figure 16. Restricted Crossing U-turn with a Single U-Turn Lane.**



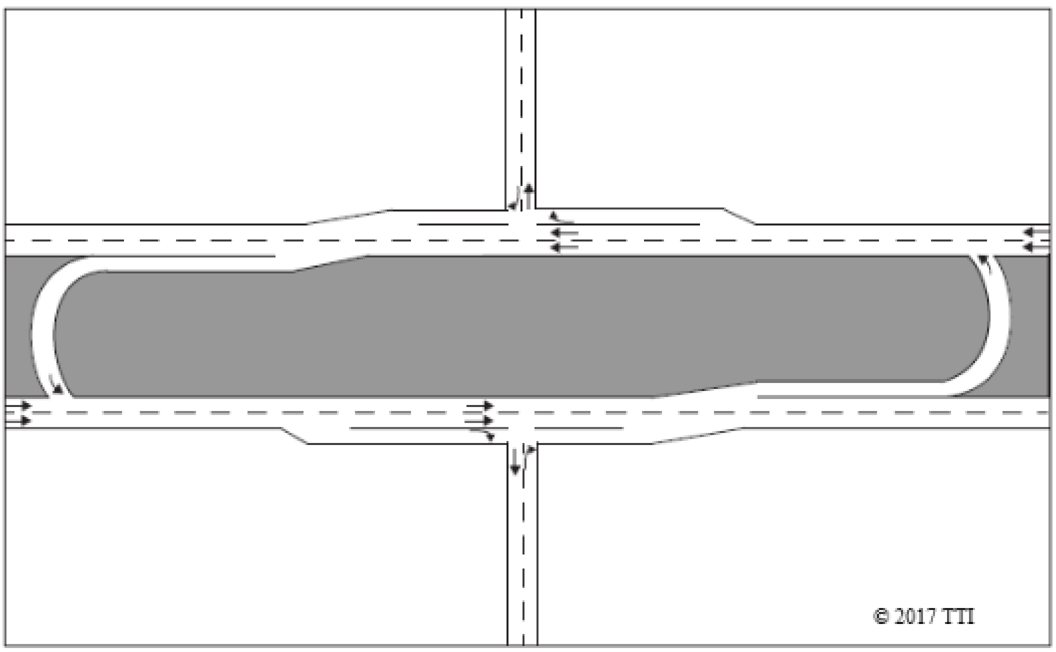

Source: Chrysler et al. (34).
**Figure 17. Restricted Crossing U-turn with a Double U-Turn Lane.**

*J-Turn Intersections*

J-turn intersections are an unsignalized version of the RCUT (*33*, *36*), although they are sometimes just referred to as a stop-controlled RCUT (*35*). Just like the RCUT, all minor road traffic turns right onto the major road. If the drivers wanted to go left or straight at the intersection, they must use the MUT crossover to continue through the intersection.




Source: ABMB Engineers (*36*).
**Figure 18. Typical J-Turn Intersection.**



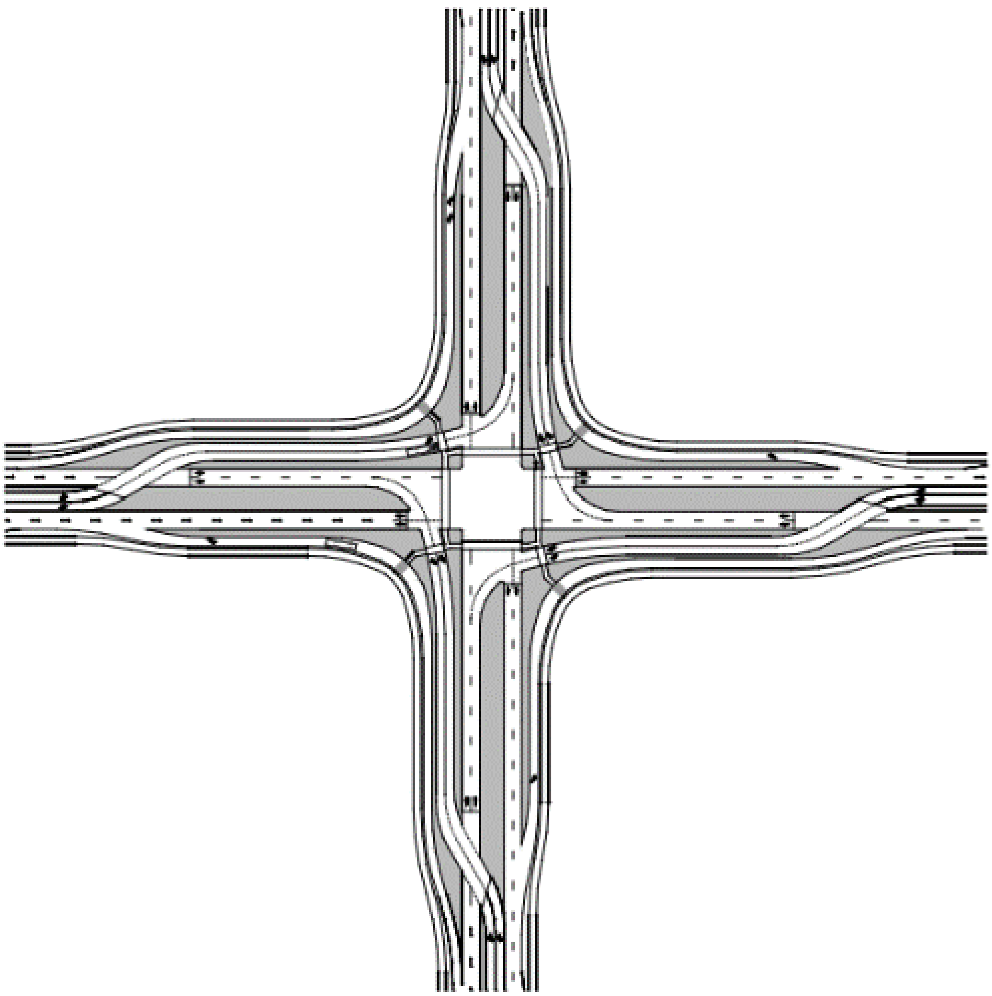

Source: Chrysler et al. (*34*).
**Figure 19. J-Turn with a Single U-Turn Lane.**

### Crossover-Based Intersections

The category of crossover-based intersections included DLTs, upstream signalized crossover intersections (USCs), and synchronized split phasing intersections (SSPs), also known as a double crossover intersection—the at-grade equivalent of a DDI. The name of the category reflects the fact that opposing directions of traffic cross each other away from the main intersection to facilitate easier turning movements. This distinction is necessary as MUTs are often referred to as crossovers.

*Displaced Left Turn Intersections*

A DLT, sometimes referred to by the misnomer of continuous flow intersection (CFI), has mainline left-turn vehicles cross over the opposing direction of traffic some distance away from the intersection. Consequently, these left turners can complete their movement at the intersection without a dedicated left-turn signal phase. An example of a DLT intersection with the displaced lanes occurring on all approaches is shown in Figure 20; however, displacement can occur on just the legs of the major road if deemed necessary.



Source: Steyn et al. (*37*).

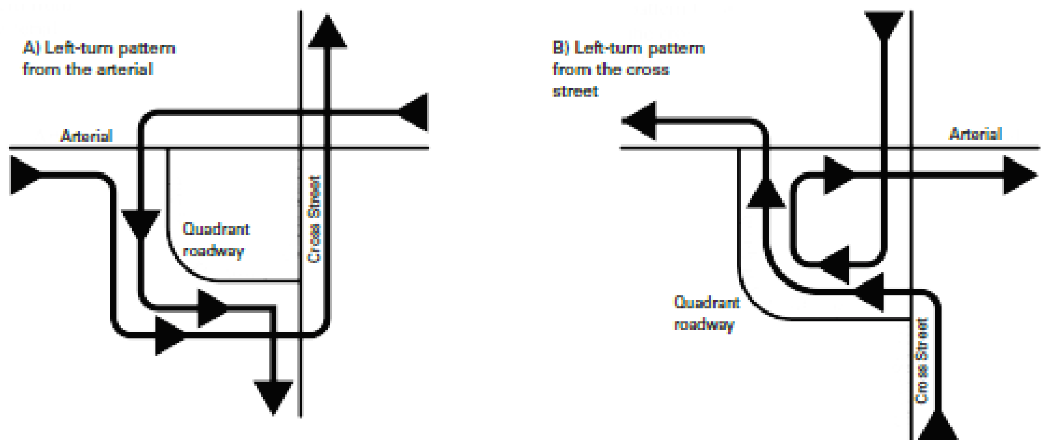
**Figure 20. Four-Leg DLT With Displaced Lefts on All Approaches.**

## Other Intersections

Other intersections include those designs that do not fit neatly into the other two categories. They can generally be thought of as designs that use multiple small intersections to more efficiently convey traffic than one big intersection.

### *Quadrant Road Intersections*

QR intersections relocate both mainline and cross-street left-turn movements to a connector roadway, moving the actual act of turning left from the main intersection (*33*, *38*). A schematic illustrating how left turns occur is shown in 21.

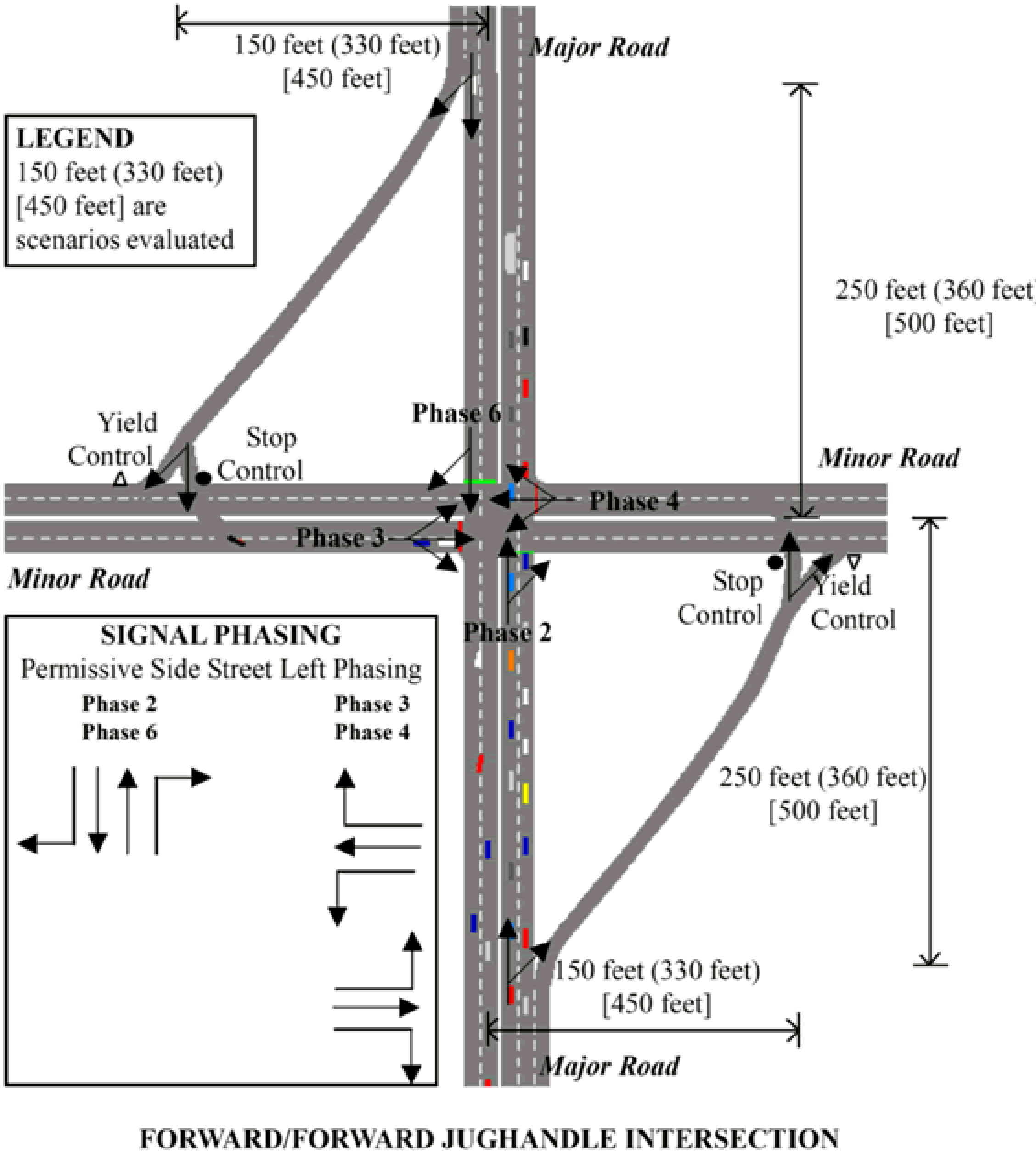



Source: Hughes et al. (*33*).

**21. Schematic Illustration of Left-Turns at a QR Intersection.**

### *Jughandle Intersections*

Jughandle intersections, also called New Jersey Jughandle Intersections, New Jersey Lefts, or Jersey Jughandles, function similarly to QRs by creating two additional intersections to move the left-turn movement away from the main intersection, however, the route is generally more direct than the QR, as illustrated in Figure 22 (*39*).

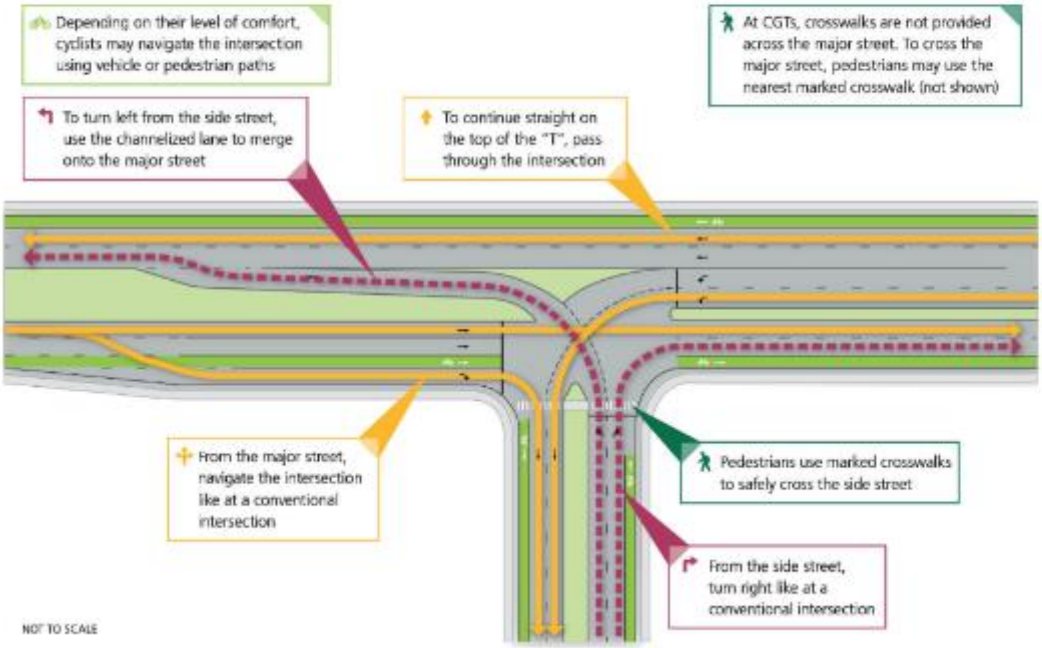



Source: FHWA (*39*).

**Figure 22. Typical Jughandle Intersection Design.**

*Continuous Green T Intersections*

CGT intersections, also known as Florida T, Turbo T, High T, and Seagull intersections, evolved as a way to reduce angle collisions at T-intersections (*40*). The intersections provide a physical barrier between left-turning vehicles and mainline vehicles, eliminating the need for one direction of mainline through traffic to stop.




Source: Virginia DOT (*41*).

**Figure 23. Navigation of a CGT Intersection.**

## REVIEW OF EXISTING RESEARCH FOR INNOVATIVE INTERSECTIONS

### U-Turn-Based Intersections

*Median U-Turns*

Autey et al. conducted a Synchro analysis of four unconventional intersection designs, including MUTs (*42*). The research team found that MUTs were generally advantageous in comparison to conventional intersections; however, some of the designs discussed later in this chapter were determined to be more effective.

One design consideration unique to MUTs as opposed to other types of U-turn-based intersections is whether or not signals should be used at the U-turn junctions. To this end, Warchol et al. provided guidance to the North Carolina Department of Transportation based on 95th percentile queue lengths in comparison to available storage space to determine when signalization was appropriate (*43*).

*Restricted Crossing U-Turns*

The safety of RCUTs was examined at several locations in Maryland (*44*). The before-and-after analysis showed a reduction in intersection crashes as well as adjacent segment crashes by 62 and 14 percent, respectively. An FHWA-funded study, also in Maryland, used video data collection to examine traffic conflicts as well as a before-and-after analysis of crash data to compare an existing RCUT with a stop-controlled intersection on the same corridor (*45*). The study found that the RCUT had fewer traffic conflicts involving vehicles entering the main road from the intersecting road, that weaving was similar between the two intersections, and that the design increased the travel time of minor street vehicles by approximately one minute. Empirical Bayes (EB) analysis of crashes found a 44 percent reduction at the RCUT.

Ozguven et al. estimated safety performance functions for RCUTs in Florida (*46*). For signalized RCUTs, the researchers indicated that the most important characteristics were the major and minor traffic volume and the number of U-turns present.

Internationally, Naghawi and Idewu published a simulation study focused on superstreets/RCUTs (*47*). Focusing on queue length and average network delay as the primary measures of effectiveness, researchers observed reductions of 97.5 percent and 27 to 82 percent, respectively.

Additional findings from the literature on the RCUT intersection is contained in the chapter on the field study of innovative intersections.

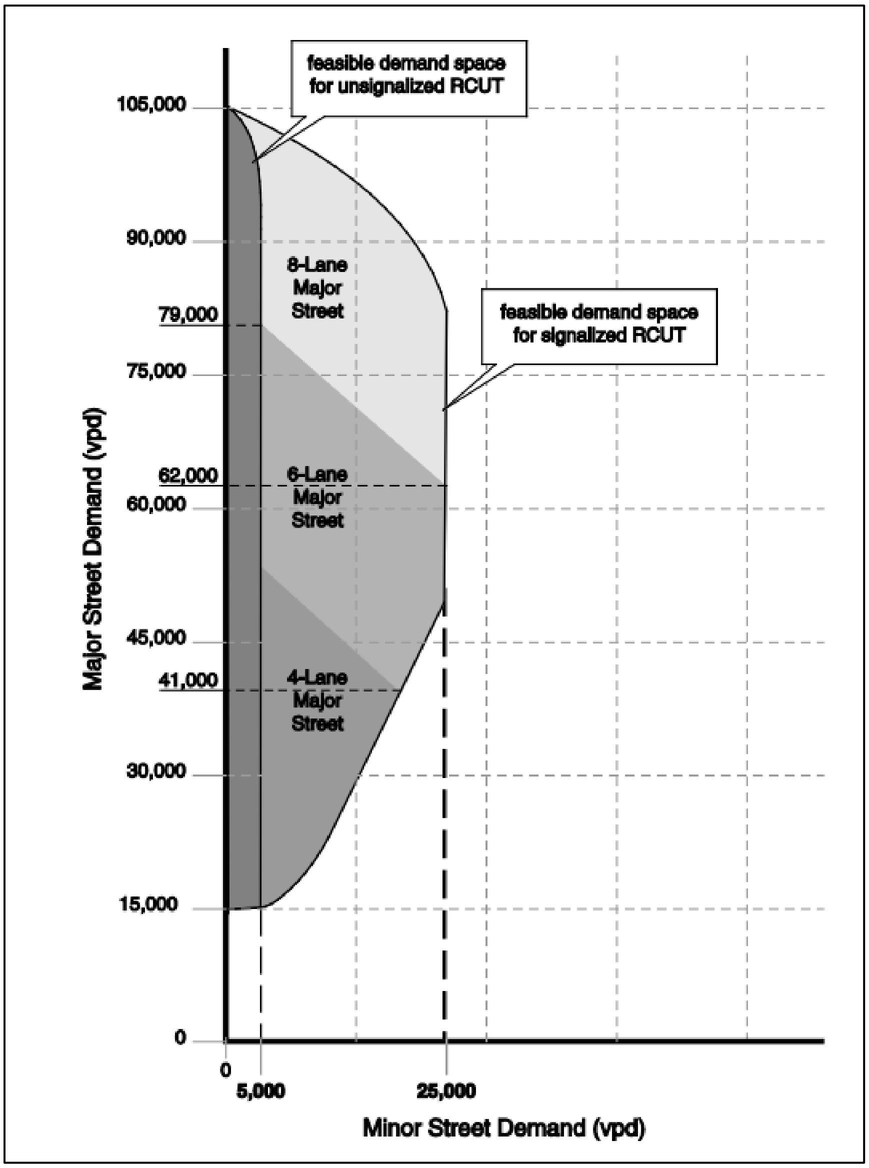
*J-Turn Intersections*

Edara et al. conducted a multi-faceted examination of J-turn intersections in Missouri (*48*). One part of that study involved a field investigation of one J-turn intersection and one conventional intersection. The researchers indicated that wait time at the J-turn site was one half that of the control site, while travel time through the J-turn intersection was approximately one minute longer.

Perry et al. examined the benefits and limitations of J-turn intersection designs through a review of existing literature (*49*). The researchers noted some of the most well-known benefits of alternative intersection designs, such as reduced conflict points, decreased crash rates of specific high-severity collision manners, equivalent or reduced travel times, and no trucker dissatisfaction, while also mentioning the higher construction costs and higher rates of rear-end collisions.

Rigorous statistical evaluation of J-turn safety was identified as a high-preference research need in NCHRP Report 650 through a focus group of representatives from various state transportation agencies (*50*). To that end, consultant researchers in Missouri evaluated the safety effectiveness of the design using an empirical Bayes before-and-after study of five J-turn locations (*48*). Based on this assessment, the researchers noted a 34.8 percent reduction of total crash frequency and a 53.7 percent reduction in fatal and injury crashes, as well as an 80 percent reduction in right-angle collision types.

To aid in the selection of RCUTs and J-turns, FHWA (*35*) has developed Figure 24 to illustrate the traffic volumes when RCUT intersections are feasible as well as when J-turns should be used.




Source: Restricted Crossing U-Turn Informational Guide, Exhibit 5-7, Page 75.

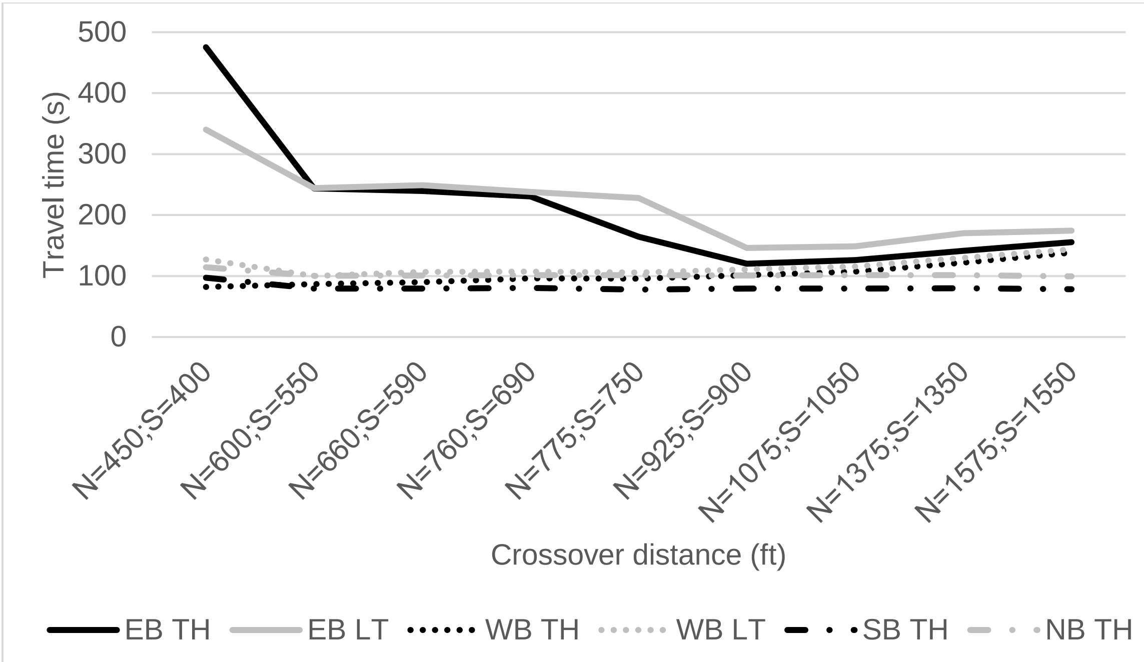
**Figure 24. Feasible Demand Space for Signalized RCUT Intersection (*35*).**

*Geometric and Signing Considerations*

Spacing is critical for U-turn-based intersections to ensure that the queue can be adequately handled, and the FHWA has noted that design guidance for RCUTs is lacking in terms of the offset required for U-turns and the need for acceleration lanes (*44*). In a Texas-based study, Qi et al. used microsimulation to assess the spacing requirements and storage lane lengths associated with the RCUT intersection at US-281 and Evans Road in San Antonio (*51*). The researchers used field-based travel time data to calibrate a base simulation of existing conditions and then compared a variety of design modifications. Regarding the spacing of the U-turns, they compared a range of values from 400 feet to 1,575 feet, noting that existing conditions were 1,075 feet on the northern leg of the intersection and 1,050 feet on the southern leg, while minimum length based on required turning lane storage length was 600 feet on the northern leg and 550 feet on the southern leg based on HCM 2010 calculation procedures. The researchers observed that mainline travel time was minimally sensitive to changes in the spacing of the U-turns except when the spacing fell below the minimum recommended values. The travel times for minor street through and left-turning vehicles was significantly different for each approach, with shorter spacing causing a noticeable increase for eastbound traffic, as illustrated in Figure 25, which synthesizes several figures presented in the Qi study.

U-turn-based intersections present a design challenge in that the median must be sufficiently wide to accommodate the design vehicle, which can range from 30 to 68 feet assuming an inner lane to inner lane turnaround (*32*).

A 2010 report funded by the Mississippi Department of Transportation summarized many design elements and criteria for the use of J-turn intersections (*36*). The treatment is primarily used on rural arterials with design speeds of 65 mph. Due to the high-speed nature of the roadways on which they are located, sight distance requirements may need to be 1,540 feet or larger. The report also describes the use of loons (i.e., bulb-outs at the MUT crossover) when median width is insufficient for the design vehicle to navigate the U-turn. From a safety standpoint, researchers in Missouri found that median U-turns spaced at least 1,500 feet from the main intersection experienced the lowest crash rates and indicated that the presence of an acceleration lane for vehicles traversing the U-turns to rejoin mainline traffic substantially reduces the number of conflicts (*52*).




Source: Graph developed based on data from Qi et al. (*51*). Note: X-axis is Labeled Based on Pairings of Distances to the North [N] and South [S] U-turn Locations.

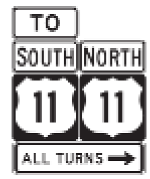
**Figure 25. Travel Time as a Function of U-Turn Spacing.**

A 2019 human factors study (*34*) used computer-based testing to investigate optimal signing sequences to guide drivers through innovative intersections that require U-turns. The first issue investigated was the sign design for the major road drivers to communicate that a left turn is prohibited and that the driver has a U-turn opportunity beyond the intersection. The signs recommended based on the study are shown in Figure 26. The recommendation for minor approaches where a left at the intersection is prohibited is to use the route sign assembly information included in the *Manual on Uniform Traffic Control Devices* (MUTCD) Section 2D.29 (Figure 27). The study found the MUTCD advance route turn assembly with a horizontal right-pointing arrow performed well (Figure 28a) as did a version of this sign with a horizontal U-turn arrow (Figure 28b) for a guide or other wayfinding sign on a minor leg with a desired but prohibited left turn at the downstream intersection.

| Junction | Advance Route Turn | Destination | Directional Assembly | Confirming |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |

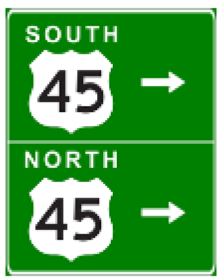
Source: Chrysler et al. (34).

**Figure 26. Recommended Treatment for Major Approaches to Intersections That Require a U-Turn Downstream of the Main Intersection.**

| Junction | Advance Route Turn | Intersection Lane Control | Directional Assembly |
| --- | --- | --- | --- |
|  |  |  |  |

Source: Chrysler et al. (34).

**Figure 27. Recommended Treatment for Minor Approaches to Intersections That Require a U-Turn.**



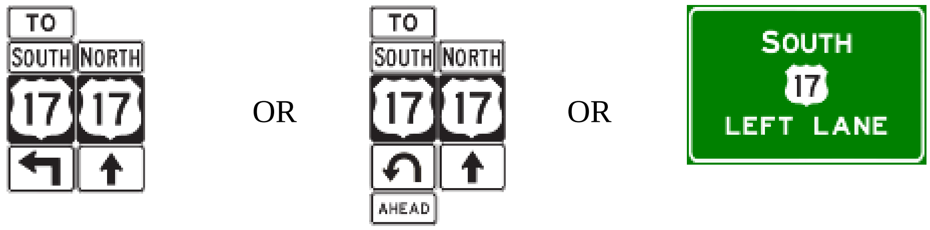

OR


(a) (b)

Source: Chrysler et al. (34)

**Figure 28. Recommended and Optional Sign for Advance Turn Assembly for Minor Leg Approach.**

The Chrysler study (*34*) conducted a state of the practice review that revealed some agencies use confirmation signs in areas with a long separation between the main intersection and the U-turn location. The computer-based testing results showed the participants indicated their lane choice sooner with any of the three sign designs shown in Figure 29. Therefore, the recommendation for confirmatory or turn direction signs downstream of the main intersection is any of these three signs. There was no difference among these signs, but each did better than no sign at all or the MUTCD route assembly with up arrows under both route markers.




Source: Chrysler et al. (34).

**Figure 29. Recommended Confirmatory or Advance Turn Signs on Major Road in Advance of the U-Turn Lane.**

### Crossover-Based Intersections

*Displaced Left Turn Intersections*

In an FHWA-sponsored informational guide, the lack of safety-focused studies on DLTs was pointed out; however, the guide acknowledged that “simultaneous movement of left-turn and through traffic at DLT intersections promotes of traffic platoons on the arterial, increases vehicular throughput, and reduces travel time along a corridor”(*37*). During the efforts to construct the informational guide, a series of microsimulations were carried out that assessed DLT effectiveness under four scenarios. The scenarios are summarized as follows:

- Intersection of a six-lane major road and a six-lane minor road with a DLT on each approach.
- Intersection of a six-lane major road and a four-lane minor road with a DLT on each major road approach.
- Intersection of a six-lane major road and a four-lane minor T-leg with a DLT on the major road.
- Intersection of a four-lane major road and a four-lane minor road with a DLT on each major road approach.

The researchers found DLTs to be associated with reductions in average delay of 19–90 percent, reductions in the number of stops under unsaturated conditions of 15–30 percent, reductions in the number of stops under saturated conditions at 85–95 percent, reduction in average queue length of 34–88 percent, and increases of throughput from 10–30 percent. Greater specificity is available in the report regarding which specific scenarios were associated with each value. Autey et al. found a four-leg intersection with DLTs on each leg to outperform MUTs, SSPs, and USCs across a wide variety of balanced and unbalanced traffic flow conditions (*42*).

## Other Intersections

### *Quadrant Road Intersections*

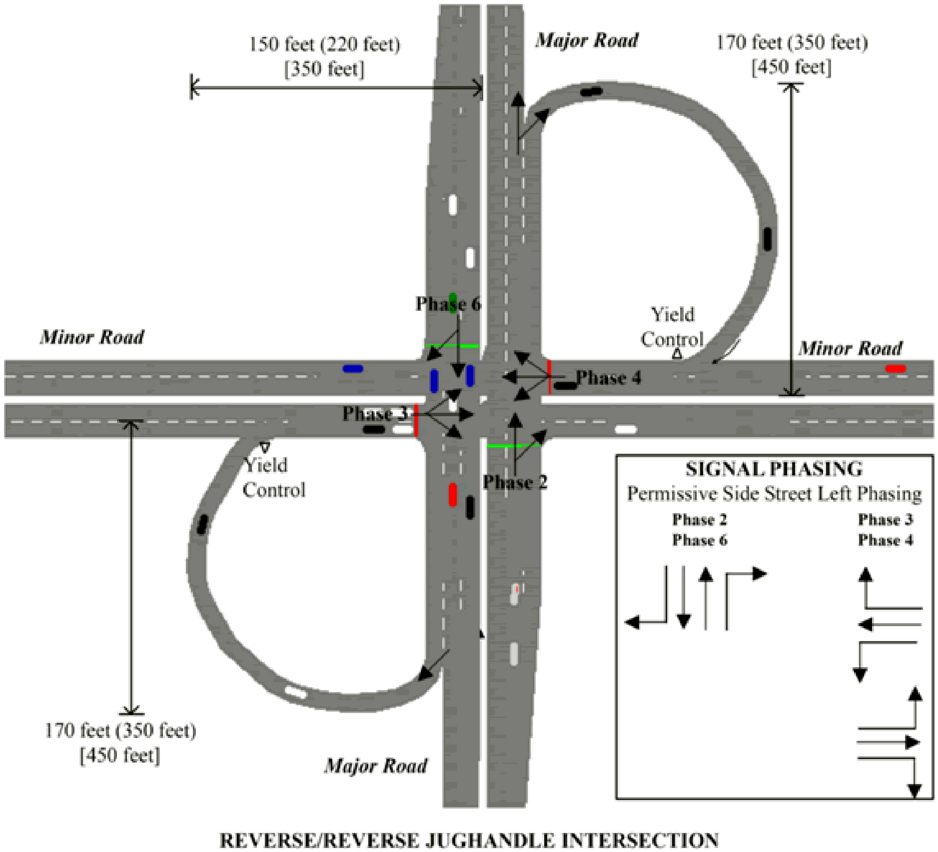
One of the challenges in examining roadway facilities that are currently minimally present on the extant transportation network is finding suitable sites for observation studies. To that end, a substantial amount of effort has been directed at using traffic microsimulation to assess the benefits of innovative intersection designs. QR intersections were associated with significant delay reductions (approximately 15 seconds per vehicle) in comparison to traditional intersections based on VISSIM modeling of an Orlando intersection (*53*).

Design advice regarding QR intersections is relatively generic. Some of the most salient suggestions by FHWA are that the location of the connector road (i.e., the quadrant in which it is located) be based on the direction of the most heavy left-turning movement to provide the most road users with the most direct path through the intersection, that the secondary intersections be positioned to provide adequate storage (typically 500 feet from the main intersection but dependent on the left-turn queue that will be expected), and that U-turns are prohibited (*48*).

### *Jughandle Intersections*

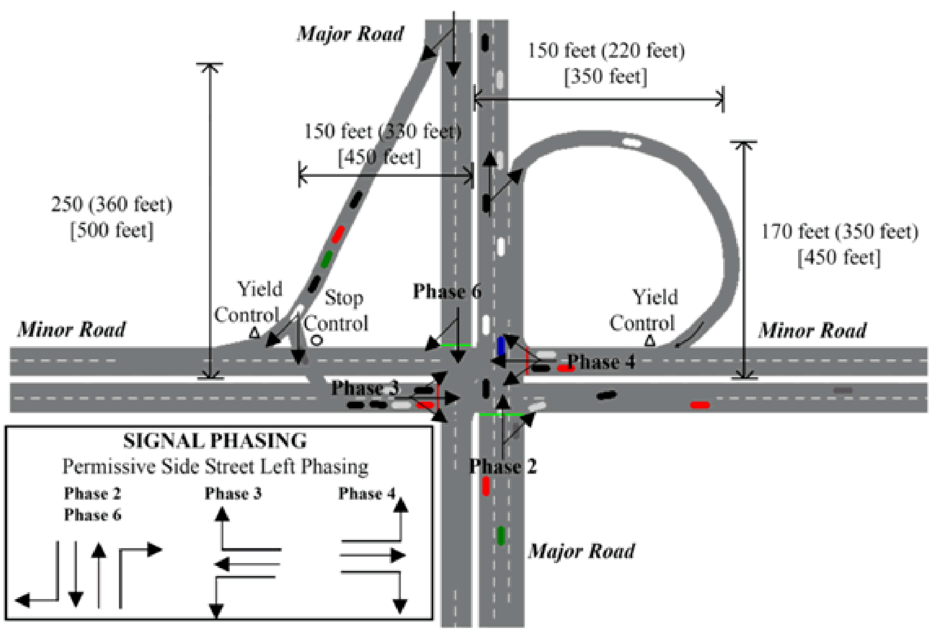
VISSIM simulations have demonstrated that the jughandle design is more efficient than conventional intersections at near-saturated conditions. Alternate jughandle intersection designs use re-directing links after vehicles pass through the main intersection or some composite of pre- and post-intersection links as shown in Figure 30 and Figure 31, respectively.

Although specific numbers were not given, Synchro simulation has indicated that the capacity of jughandle intersections decreases as the offset between the main intersection and secondary intersections decreases (*39*). This is relatively intuitive; excessive queuing could potentially spill over from the sub-intersections to the main intersection or vice versa.




Source: FHWA (*39*).

**Figure 30. Jughandle Located After the Main Intersection.**




Source: FHWA (*39*).

**Figure 31. Combination Pre/Post-Intersection Jughandle.**

*Continuous Green T Intersections*

An FHWA case study investigated two T-intersections in Colorado that were replaced with CGTs (*40*). Using two years of before data and two years of after data, the crash totals at the two intersections fell by 56.3 and 63.2 percent, angle collisions at the intersections were virtually eliminated (100 percent and 93.3 percent reductions), and injury crashes were reduced by 83.3 and 50 percent.

## REVIEW OF STATE DOCUMENTS

### Guidance

Table 4 presents information where formal documents or websites maintained by state or other government sources indicate circumstances when innovative intersection designs can be used or describe design criteria for such designs.

**Table 4. State-Level Guidance Documents (Denoted by Citation Number).**

| State | Design Guides | | | Selection Aid |
|---|---|---|---|---|
| | **U-Turn-Based** | **Crossover-Based** | **Other** | |
| Arizona | — | — | *54* | — |
| California | — | — | *55* (SPUI) | — |
| Florida | — | — | — | *56*, *57* |
| Georgia | *58* (RCUT) | *58* (DDI) | — | *59*, *60* |
| Indiana | *61* (MUT) | — | — | *96* |
| Illinois | — | *62* (DDI) | *62* (SPUI) | *63* |
| Kentucky | *64* (Overview of several intersection types) | *64* | *64* | — |
| Maryland | — | — | — | *65* |
| Michigan | *66* (Crossovers), *67* (MUT) | — | — | *67* |
| Missouri | — | *68* (DDI) | — | — |
| Montana | *69* (MUT, RCUT) | *69* (DLT, DDI) | — | — |
| Nevada | *70* | — | — | — |
| New Jersey | — | — | *71* (Jughandle) | — |
| South Carolina | *72* | *72* | *72* | — |
| Virginia | *41* | *41* | *41* | — |
| Utah | — | *73* (DLT), *74* (DDI) | — | — |
| Washington | — | — | — | *75* |

*Note: — = not applicable. Guidance for category is general unless otherwise specified.*

The level of guidance varies state by state. For example, Michigan has a *Road Design Manual (66*) and an *Intersection Design Guide* (*67*); the former focuses on the median openings while the latter provides volume guidance when MUTs should be implemented. Two documents published by the Utah Department of Transportation focus on specific types of facilities (*73*, *74*). In other cases, such as Nevada, these documents simply point to federal information on the topic (*70*).

## Research

Many state departments of transportation, as well as the federal government, have funded research regarding innovative intersections. While these documents often provide recommendations regarding aspects of innovative intersection design, they are not formal policy documents. A table documenting the type of intersection that has been studied within a state is shown in Table 5.

**Table 5. State and Federal Research Documents (Denoted by Citation Number).**

| State | Design Guides | | | Selection Aid |
|---|---|---|---|---|
| | U-Turn Based | Crossover-Based | Other | |
| Florida | *53* (MUT), *46* (RCUT) | *53* (DDI, DLT) | — | — |
| Idaho | *76* (RCUT) | — | — | — |
| Indiana | *77* (MUT), *97* (MUT) | *77* (DDI), *97* (DLT,) | *97* (Jughandle) | *78* |
| Kentucky | — | — | — | *94* |
| Louisiana | — | *79* (DLT) | — | |
| Maryland | — | *91* (DLT, DDI), *92* (DDI) | — | *91* |
| Michigan | *80* | — | — | — |
| Minnesota | *81* (MUT) | — | *82* (CGT) | — |
| Mississippi | *36* (J-Turn) | — | — | — |
| Missouri | *48* (J-Turn), *52* (J-Turn) | *83* (DDI), *84* (DDI) | — | — |
| Nebraska | *93* (MUT) | *93* (CFI, Jughandle) | — | — |
| North Carolina | *43* (MUT) | — | — | — |
| Texas | *51* (RCUT, MUT) | *51* (DLT) | — | — |
| Utah | — | *85* (DDI), *86* (DDI, DLT) | — | — |
| Wisconsin | *49* (J-turn) | — | — | — |
| United States | *45* (RCUT), *50*, *87* | *50*, *88* (DLT), *89* | *50* | *50* |

*Note: — = not applicable. Research conducted on category is general unless otherwise specified.*

## REVIEW OF DOCUMENTS FROM FHWA WEBSITE

FHWA, through their safety initiative known as "Every Day Counts," has noted that in 2009 there were 33,808 roadway fatalities in the United States, and that 20 percent of the fatalities were at intersections or were intersection-related. While there have been success stories over the past 25 years in areas where fatalities have been reduced, the relationship of total fatalities to intersection or intersection-related fatalities has not changed greatly. At the national level, implementation of innovative intersections and interchanges has occurred steadily in the recent past (*90*). Due to the capacity and safety benefits associated with innovative intersections, FHWA is promoting several emerging innovative intersections through various media formats on its website. The following list includes all available information readily available through the FHWA website, as well as other information the research team identified.

### Information Videos

*U-Turn-Based*

- Alternative Intersections: Median U-Turns Informational Video (FHWA) https://www.youtube.com/watch?v=fshW_O_XggI
- Alternative Intersections: Restricted Crossing U-Turn Informational Video (FHWA) https://www.youtube.com/watch?v=BLwl01NCp9I
- Video Case Study: Median U-Turn—Michigan Avenue at South Harrison Road, East Lansing, MI (FHWA) https://www.youtube.com/watch?v=fiEhiNyQ4Oo
- Video Case Study: Median U-Turn—Woodward Avenue at East Maple Road, Birmingham, MI (FHWA) https://www.youtube.com/watch?v=TYJ0jLXF4Cw
- Video Case Study: Median U-Turn—Statewide Corridor Applications, State of Michigan (FHWA) https://www.youtube.com/watch?v=rvazA22vhN0
- Video Case Study: Restricted Crossing U-Turn—US-15 Corridor, Frederick County, MD (FHWA) https://www.youtube.com/watch?v=ffnrsQ1rGic
- Video Case Study: Restricted Crossing U-Turn—State Route 55 Bypass, Holly Springs, NC (FHWA) https://www.youtube.com/watch?v=AxIiLzv-GOA

- Video Case Study: Restricted Crossing U-Turn—US-17 Corridor, Wilmington/Leland, NC (FHWA) https://www.youtube.com/watch?v=LB5nTDSVEzs
- Reduced Conflict Intersection: A Safer Alternative (MnDOT) https://www.youtube.com/watch?v=c5pBnuu1Cno
- RCUT semitrailer visualization (MnDOT) https://www.youtube.com/watch?v=ZduD-EYH8qw
- Understanding Reduced Conflict Intersections (MnDOT) https://www.youtube.com/watch?time_continue=4&v=M8j4aM3C7yY&feature=emb_logo
- Hwy 65, Reduced Conflict Intersection (MnDOT) https://www.youtube.com/watch?v=2SqQDfh4s1g
- Missouri DOT—"What is a J-Turn" Video https://www.youtube.com/watch?v=Kfu6yx9kgCY

*Crossover-Based*

- Alternative Intersections: Diverging Diamond Interchange Informational Video (FHWA) https://www.youtube.com/watch?v=eLAwwl3EtN4
- Alternative Intersections: Displaced Left Turn Intersection Informational Video (FHWA) https://www.youtube.com/watch?v=3wIv0a9fuB0&index=9&list=PL5_sm9g9d4T0VisDAyJpyQDTM1BuqUUjA
- Video Case Study: Diverging Diamond Interchange—I-44 at State Route 13, Springfield, MO (FHWA) https://www.youtube.com/watch?v=R45zqZBxs-k
- Video Case Study: Diverging Diamond Interchange—I-15 at Main Street, American Fork, UT (FHWA) https://www.youtube.com/watch?v=zyL2Qhm372Y
- Video Case Study: Diverging Diamond Interchange—I-15 at State Route 92/Timpanogos Hwy, Lehi, UT (FHWA) https://www.youtube.com/watch?v=4p7lvRzh9Gs
- Video Case Study: Displaced Left Turn—State Route 30 at Summit Drive, Fenton, MO https://www.youtube.com/watch?v=l6I5AJRHsQc

- Video Case Study: Displaced Left Turn—Bangerter Highway Corridor, Salt Lake County, UT https://www.youtube.com/watch?v=o5-U_TgEtJA
- Video Case Study: Displaced Left Turn—Redwood Road at 6200 South, Taylorsville, UT https://www.youtube.com/watch?v=eKAONboIzao
- Utah DOT—Innovative Intersections and Interchanges Videos https://www.youtube.com/playlist?list=PLIUbVJOQ00BoDFRBSeIJWXnYnP9si7HwF
- Mississippi DOT Diverging Diamond Interchange in D'Iberville on Interstate 10 https://www.youtube.com/watch?v=Afw-vrwagW0

*Other Intersections*

- North Carolina DOT—Quadrant Roadway Video https://www.youtube.com/watch?v=ZtIL2GqQJbs
- Ohio DOT—Quadrant Roadway Video https://www.youtube.com/watch?v=Vk9Io8q_58w
- Virginia DOT—Quadrant Roadway Video https://www.youtube.com/watch?v=D0EU07YJYC4
- KNA Quadrant Model https://www.youtube.com/watch?v=6ZNtV3Aflrc&feature=youtu.be

**Informational Brochures**

- Alternative Intersections: Median U-Turn Intersection (FHWA) https://safety.fhwa.dot.gov/intersection/innovative/uturn/brochures/mut_brochure/
- Alternative Intersections: Restricted Crossing U-Turn Intersection (FHWA) https://safety.fhwa.dot.gov/intersection/innovative/uturn/brochures/rcut_brochure/
- Alternative Intersections: Diverging Diamond Interchange (FHWA) https://safety.fhwa.dot.gov/intersection/innovative/crossover/brochures/ddi/
- Alternative Intersections: Displaced Left Turn Intersection (FHWA) https://safety.fhwa.dot.gov/intersection/innovative/crossover/brochures/dlt/

## Informational Case Studies

*U-Turn-Based*

- Minnesota's First Restricted Crossing U-Turn Intersections (J-Turns) https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/mn/
- North Carolina's Experience with Restricted Crossing U-Turn Superstreets https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/nc/
- Case Study Fact Sheet: Median U-Turn—Michigan Avenue at South Harrison Road, East Lansing, MI https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/mi/east_lansing/
- Case Study Fact Sheet: Median U-Turn—Woodward Avenue at East Maple Road, Birmingham, MI https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/mi/birmingham/
- Case Study Fact Sheet: Median U-Turn—Statewide Corridor Applications, MI https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/mi/detroit/
- Case Study Fact Sheet: Restricted Crossing U-Turn—US-15 Corridor, Frederick County, MD https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/md/
- Case Study Fact Sheet: Restricted Crossing U-Turn—State Route 55 Bypass, Holly Springs, NC https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/nc/holly_springs/
- Case Study Fact Sheet: Restricted Crossing U-Turn—US-17 Corridor, Wilmington/Leland, NC https://safety.fhwa.dot.gov/intersection/innovative/uturn/case_studies/nc/wilmington/
- Georgia’s First Restricted Crossing U-Turn Intersections https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/ga/

*Crossover-Based*

- Case Study Fact Sheet: Diverging Diamond Interchange—I-44 at State Route 13, Springfield, MO https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/mo/
- Case Study Fact Sheet: Diverging Diamond Interchange—I-15 at Main Street, American Fork, UT https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/ut/index.cfm
- Case Study Fact Sheet: Diverging Diamond Interchange—I-15 at State Route 92/Timpanogos Hwy, Lehi, UT https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/lehi/index.cfm
- Case Study Fact Sheet: Displaced Left Turn—State Route 30 at Summit Drive, Fenton, MO https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/fenton/index.cfm
- Case Study Fact Sheet: Displaced Left Turn—Bangerter Highway Corridor, Salt Lake County, UT https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/salt_lake/index.cfm
- Case Study Fact Sheet: Displaced Left Turn—Redwood Road at 6200 South, Taylorsville, UT https://safety.fhwa.dot.gov/intersection/innovative/crossover/case_studies/redwood/index.cfm

*Other Intersections*

- Continuous Green T-Intersections https://safety.fhwa.dot.gov/intersection/innovative/others/casestudies/fhwasa09016/

### Public Roads Magazine Articles

- "The ABCs of Designing RCUTs." Sep/Oct 2014, Vol. 78, No. 2 https://www.fhwa.dot.gov/publications/publicroads/14sepoct/02.cfm
- "Design at the Crossroads." Jul/Aug 2013, Vol. 77, No. 1 https://www.fhwa.dot.gov/publications/publicroads/13julaug/01.cfm
- "North Carolina Steps Boldly Out of Its Comfort Zone." Jul/Aug 2013, Vol. 77, No. 1 https://www.fhwa.dot.gov/publications/publicroads/13julaug/04.cfm
- "The Double Crossover Diamond." Nov/Dec 2010, Vol. 74, No. 3 https://www.fhwa.dot.gov/publications/publicroads/10novdec/01.cfm
- "A New Left Turn." Jul/Aug 2009, Vol. 73, No. 1 https://www.fhwa.dot.gov/publications/publicroads/09julaug/04.cfm
- "Design at the Crossroads." Jul/Aug 2013, Vol. 77, No. 1 https://www.fhwa.dot.gov/publications/publicroads/13julaug/01.cfm

### Technical Materials

- Alternative Intersections/Interchanges Informational Report (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09060/index.cfm

*U-Turn-Based*

- Reduced Left-Turn Conflict Intersections Summary (FHWA, 2018) https://safety.fhwa.dot.gov/intersection/innovative/uturn/fhwasa18048/
- Reduced Left-Turn Conflict Intersections (Proven Safety Countermeasure) (FHWA, 2017) https://safety.fhwa.dot.gov/provencountermeasures/reduced_left/
- Median U-Turn Intersection Informational Guide (FHWA, 2014) https://safety.fhwa.dot.gov/intersection/rltci/fhwasa14069.pdf
- Restricted Crossing U-Turn Intersection Informational Guide (FHWA, 2014) https://safety.fhwa.dot.gov/intersection/rltci/fhwasa14070.pdf
- Median U-Turn Intersection TechBrief (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09057/index.cfm
- Restricted Crossing U-Turn TechBrief (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09059/

- Synthesis of the Median U-Turn Intersection Treatment (FHWA, 2007) https://www.fhwa.dot.gov/publications/research/safety/07033/

*Crossover-Based*

- Diverging Diamond Interchange Informational Guide, Second Edition (NCHRP, 2021) https://www.trb.org/Main/Blurbs/181562.aspx
- Displaced Left Turn Intersection Informational Guide (FHWA, 2014) https://safety.fhwa.dot.gov/intersection/alter_design/pdf/fhwasa14068_dlt_infoguide.pdf
- Double Crossover Diamond Interchange TechBrief (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09054/index.cfm
- Displaced Left Turn Intersection TechBrief (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09055/
- Displaced Left Turn Interchange TechBrief (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09056/

*Other Intersections*

- Quadrant Roadway Intersection Fact Sheet (FHWA, 2009) https://www.fhwa.dot.gov/publications/research/safety/09058/
- Traffic Performance of Three Typical Designs of New Jersey Jughandle Intersections (FHWA, 2007) https://www.fhwa.dot.gov/publications/research/safety/07032/

**Other Resources**

- National Highway Institute Course #380109 "Alternative Intersections & Interchanges" https://www.nhi.fhwa.dot.gov/course-search?tab=0&key=alternative+intersections&sf=0&course_no=380109
- Capacity Analysis for Planning of Junctions (CAP-X) Tool https://www.fhwa.dot.gov/software/research/operations/cap-x/
- Every Day Counts 2—Intersection & Interchange Geometrics Initiative Resources https://www.fhwa.dot.gov/innovation/everydaycounts/

- Virtual Exchange for Local and Tribal Agencies (December 2013) https://www.fhwa.dot.gov/innovation/resources/presentations.cfm#edc_exchange
- Transportation Research Board Alternative Intersection/Interchange Symposium Proceedings (via TeachAmerica) http://teachamerica.com/ai14/
- Innovative Intersections—DDI Informational Guide Webinar https://connectdot.connectsolutions.com/p1vqqq510ht/?proto=true
- Innovative Intersections—DLT/MUT/RCUT Informational Guides Webinar https://connectdot.connectsolutions.com/p7zva68mrmq/?proto=true
- Missouri Department of Transportation—Highway Features https://www.modot.org/highway-features-0
- New York State Department of Transportation I-590 Winton Rd. Interchange Project https://www.dot.ny.gov/regional-offices/region4/projects/590winton/diverging-diam
- North Carolina Department of Transportation—Safety & Mobility https://www.ncdot.gov/initiatives-policies/Transportation/safety-mobility/Pages/default.aspx
- Oklahoma Department of Transportation—Elk City's Diverging Diamond Interchange at I-40 & SH-6 https://oklahoma.gov/odot/citizen/major-projects/completed-projects/i-40-and-sh-6-diverging-diamond-interchange.html
- South Dakota Department of Transportation—Diverging Diamond Interchange https://dot.sd.gov/projects-studies/sddot-innovation/diverging-diamond-interchange
- Texas Department of Transportation—Innovative Intersection Design https://static.tti.tamu.edu/conferences/tsc15/presentations/design/valtier.pdf
- I-39/90 Expansion Project
  - https://wisconsindot.gov/pages/safety/safety-eng/inter-design/ddi.aspx
  - https://projects.511wi.gov/i-39-90/wp-content/uploads/sites/145/I39-90andWIS11AvalonRoadDDI-FAQ.pdf
  - https://projects.511wi.gov/i-39-90/wp-content/uploads/sites/145/I39-90andWIS11AvalonRoadDDI-LargeTrucks.pdf

## INTERSECTION SELECTION

### General

As with any technology that is not already widely used, there is a need to assess when and where specific intersection designs are applicable and where they have deficiencies. Focusing on identifying deficiencies, Chang et al. developed a software tool that used queue estimation models and delay computations to conduct planning-level assessments of CFIs and DDIs (*91*). The researchers noted that queue spillback at the sub-intersections can gridlock the overall design. Building on that report, Yang et al. used field studies of two sites in Maryland to calibrate a CFI simulation experiment (*92*). The researchers indicated queue length ratio (the ratio of the maximum queue to the available storage bay length) as the critical variable due to its ability to allow researchers to identify any queue spillback locations.

A 2014 report by Sharma et al. used HCS 2010 to estimate delay and subsequently conduct an economic analysis on MUTs, CFIs, and jughandles (*93*). The researchers noted that MUTs were reasonable for most traffic splits between major and minor streets when left-turning traffic volume was relatively low, but that CFIs and jughandles performed better for higher left-turning volumes, with CFIs performing better when major and minor traffic were balanced and jughandles when major and minor traffic were unbalanced.

In Kentucky, Stamatiadis and Kirk developed a macro-based Intersection Design Alternative Tool for the Kentucky Transportation Cabinet (*94*, *95*). The tool uses intersection movement traffic volumes as the primary input and implements a weighted scoring formula to account for right-of-way considerations, pedestrian, bicyclist, and motorist safety, and access management near the intersection.

To facilitate the use of innovative intersection designs, the Indiana Department of Transportation has developed a decision guide outlining a two-stage intersection selection process (*96*). The preliminary stage is primarily regarding the feasibility of each design, while the secondary stage requires the designer to assess each feasible alternative qualitatively to select the best feasible alternative.

Additional research by Tarko et al. used Indiana-calibrated VISSIM models to assess the traffic scenarios under which specific alternative intersection designs might be useful (*97*). The analysis indicated that MUT and CFI intersections are the most promising designs for alleviating delay caused by heavy traffic volumes.

FHWA (*98*) summarized their innovative intersection design program including providing a graph showing the cumulative number of states deploying at least one innovative intersection design. As of 2018, 30 states have implemented a diverging diamond, 12 states a MUT, 14 states a RCUT, and 13 states a DLT.

### Intersection Control Evaluation Tool

With the dozens of conventional and innovative intersection types and variations proven to work in the United States, FHWA has developed the Intersection Control Evaluation (ICE) tool. ICE is a data-driven, performance-based framework and approach used to objectively screen alternatives and identify an optimal geometric and control solution for an intersection (*99*).

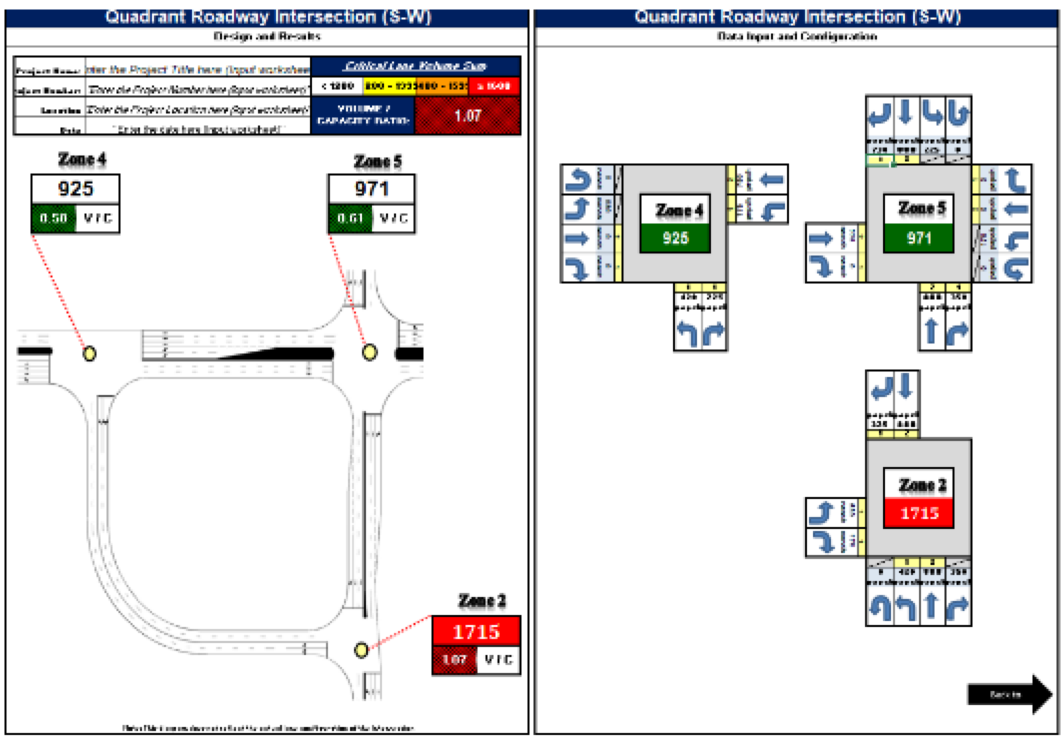
FHWA notes that utilizing ICE policies and procedures to evaluate and select the geometry and control for an intersection offers many potential benefits to road agencies and the traveling public, including:

- Implementation of safer, more balanced, and more cost-effective solutions.
- Consistent documentation that improves the transparency of transportation decisions.
- Increased awareness of innovative intersection solutions and emphasis on objective performance metrics for consistent comparisons.
- The opportunity to consolidate and streamline existing intersection-related policies and procedures, including access or encroachment approvals, new traffic signal requests, and impact studies for development.

The ICE process is typically conducted in two stages:

- A "Stage I—Scoping" step to determine the short list of all possible alternatives that merit further consideration and analysis because they meet project needs and are practical to pursue.
- A "Stage II—Alternative Selection" step to determine the preferred alternative based on more detailed evaluations conducted during typical preliminary engineering activities.

A growing number of transportation agencies are developing and adopting ICE policies. Georgia, for instance, has several documents outlining how the ICE procedure is to be implemented (*59*, *60*). As an example of how ICE is applied in practice, a corridor study prepared for the Wyoming DOT highlights the range of design alternatives, innovative intersections included, that were evaluated as part of a project involving several state highways (*100*). Although there are differences among these ICE policies, they are consistent in emphasizing transparency, flexibility, and adaptability. In addition to the establishing the ICE framework, FHWA has spearheaded efforts to develop planning-level tools to determine the feasibility of alternative intersection designs, including the Excel-based Capacity Analysis for Planning of Junctions (Cap-X) Tool (*101*) and previously the Alternative Intersection Selection Tool, both of which evaluate intersections, roundabouts, and interchanges on the basis of peak flow volumes. An example of the output format of Cap-X is shown in Figure 32.




Source: FHWA (*101*).

**Figure 32. Example Output from Cap-X Tool.**

### Pedestrians and Bicyclists at Innovative Intersections

NCHRP Research Report 948, *Guide for Pedestrian and Bicyclist Safety at Alternative and Other Intersections and Interchanges* (*102*), provides specific guidance for four common innovative intersections and interchanges: diverging diamond interchange, restricted crossing U-turn, median U-turn, and displaced left-turn. In addition, the guide provides a principles-based approach that is applicable to any innovative intersection and conventional intersection forms.

NCHRP Report 948 complements the ICE process in providing quantitative and qualitative techniques to establish initial design decisions and to evaluate the performance of alternatives. It presents three major categories of assessment tools:

- Facility design elements, used during Stage 1 to identify basic pedestrian and bicyclist facility types and routing.
- Quantitative evaluation techniques, used during both Stages 1 and 2 to assess the quality of service and level of comfort.
- Design flags, used during Stage 2 to assess safety, accessibility, comfort, and operational aspects for each mode.

The Design Flag method is the core of the NCHRP Report 948 assessment. Each alternative is evaluated for 20 conditions, such as the presence of motor vehicle right turns, indirect paths for the pedestrian, or bicycle clearance times. The researchers used focus groups, surveys, and expert opinions to develop a method that scores each crosswalk and bicyclist movement at an intersection on 20 different aspects. Each of the 20 aspects can be scored as "no flag," meaning no unusual concern about that aspect of the pedestrian or bicyclist movement, a "yellow flag," meaning concern that that aspect of the movement could be inconvenient or uncomfortable, or a "red flag," meaning concern that that aspect of the movement could lead to more crashes. NCHRP Report 948 provided detailed descriptions of each of the 20 aspects and criteria for what earns a yellow or red flag. The number and type of flags present for the various alternatives being considered can be compared to identify which alternatives should be advanced.

To aid in identifying potential intersection designs, Hummer (*103*) developed a safest feasible intersection design (SaFID) for each combination of major and minor street size and demand. The tables are dominated by four designs, including all-way stop control, roundabouts, reduced conflict intersections, and median U-turns. He noted that the tables reflect current knowledge in safety along with being limited to the conditions reflected. For example, the tables he developed apply to four-leg intersections and may not apply to a project improving a three-leg intersection.

Hummer also created tables to illustrate optimum feasible intersection design for pedestrians and bicyclists (*104*). Hummer used the ideas from NCHRP Report 948 and his SaFID tables to generate tables for optimum feasible intersection designs for pedestrians and for bicyclists. Table 6 shows a copy of the table created for pedestrians. The tables are to give planners and designers a default concept for a particular location that could be the starting place for detailed analysis.

**Table 6. Pedestrian Optimum Feasible Intersection Design per Hummer (*104*).**

| | Minor #Ln | 2 | 2 | 2 | 2 | 4 | 4 | 6 or 8 |
|---|---|---|---|---|---|---|---|---|
| Major #Ln | ADT Ranges | 0–5000 | 5000–7500 | 7500–10,000 | 10,000–15,000 | 10,000–25,000 | 25,000 and above | Any |
| 2 | 0–7500 | AWSC | AWSC | N/A | N/A | N/A | N/A | N/A |
| 2 | 0–7500 | Round | Round | Round | Round or Signal | N/A | N/A | N/A |
| 4 | 10,000–15,000 | TWSC or Signal | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | N/A | N/A |
| 4 | 15,000–20,000 | TWSC or Signal | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | N/A | N/A |
| 4 | 20,000–25,000 | TWSC or Signal | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | N/A | N/A |
| 4 | 25,000 and above | TWSC or Signal | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | MUT | N/A |
| 6 or 8 | Any | TWSC or Signal | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | Bowtie or MUT | MUT | MUT |

*Note: N/A = not applicable. AWSC = all-way stop control. Bowtie = pair of two roundabouts (looks like a bowtie in aerial view). Round = roundabouts. Signal = traffic control signal. TWSC = two-way stop control.*

## EXAMPLES OF PROVEN TREATMENTS

While the use of innovative intersections in Texas is rare but growing, TxDOT does have previous experience in successfully adopting several innovative design features that have been implemented across the state. One such example is use of U-turns at diamond interchanges (*105*), which were studied by Texas A&M Transportation Institute in terms of safety and operation. That research team made recommendations when the use of such U-turns was appropriate based on traffic volume. Ultimately, that study emphasized the need for engineers to be able to implement context sensitive solutions to solve safety and operational challenges. Other examples of innovative intersection/interchange designs that have become broadly accepted is the SPUI and the roundabout.

# CHAPTER 4: FIELD STUDY OF ROUNDABOUT INTERSECTIONS

This chapter summarizes the findings from Task 2 efforts to identify potential study sites and from Task 6, which included final selection of those sites, field data collection, and microsimulation of a variety of intersection and traffic configurations related to roundabout operations. The field data collection effort included identifying potential study sites for roundabouts with high-speed approaches, rural locations, and/or heavy vehicle volumes; selecting appropriate sites for data collection; developing and executing a field data collection plan; and reducing the field data. Data were collected at three locations, one in Texas and two in Kansas, with in-state data collected through traditional methods (i.e., ground-based video recording, lidar speed guns, and traffic classifiers) and out-of-state data collected by unmanned aerial vehicle (i.e., drone). The data collected through the drone-based video footage were reduced and used to develop microsimulation models to evaluate operational performance of roundabouts with varying inscribed circle diameters as well as two-way stop-controlled intersections with multiple levels of traffic volumes, heavy vehicle percentages, and OSOW vehicle percentages.

## REVIEW OF POTENTIAL STUDY SITES

To compile a list of potential study sites for Task 2 of this project, the research team started with sites known to the project team members and supplemented that with site information found on the Online Inventory Database of Roundabouts and Other Circular Intersections (*106*). This database, hosted by Kittelson & Associates as a service for the Transportation Research Board Roundabouts Committee, contained records of over 9,800 roundabouts worldwide at the time of this project. Using this database, researchers obtained limited information on 189 roundabouts within Texas, as shown in Figure 33. From there, researchers worked to collect more detailed information for all prospective study sites. This was done primarily by using TxDOT's 2017/2018 Roadway Highway Inventory Network Offload (RHINO) database.

Desired site characteristics included the following:

- Rural environment = Is the intersection in a rural (or suburban) area?
- High-speed approaches = Does at least one approach have a posted speed limit (PSL) of at least 45 mph?

- Trucks = Does the intersection serve a high estimated truck percentage at the intersection, and/or does it serve OSOW vehicles?

Thus, researchers reviewed the maximum approach PSL and the percent of truck traffic for each roundabout. When possible, the PSLs were verified using Google Earth Street View. Researchers applied particular focus on sites believed to serve high volumes of OSOW vehicles in rural areas and/or with high approach speeds. Because the number of sites meeting these criteria were small, other sites were selected for having useful characteristics to study. For each of these sites, the research team collected additional and more detailed site information and created a summary spreadsheet list with all the site-specific details for each site. Researchers ultimately compiled a list of 13 sites in Table 7, provided to show a sample of the information collected to that point; not all of these sites had the same potential to be chosen as study sites, but they showed examples of roundabout intersections currently in operation in the state.

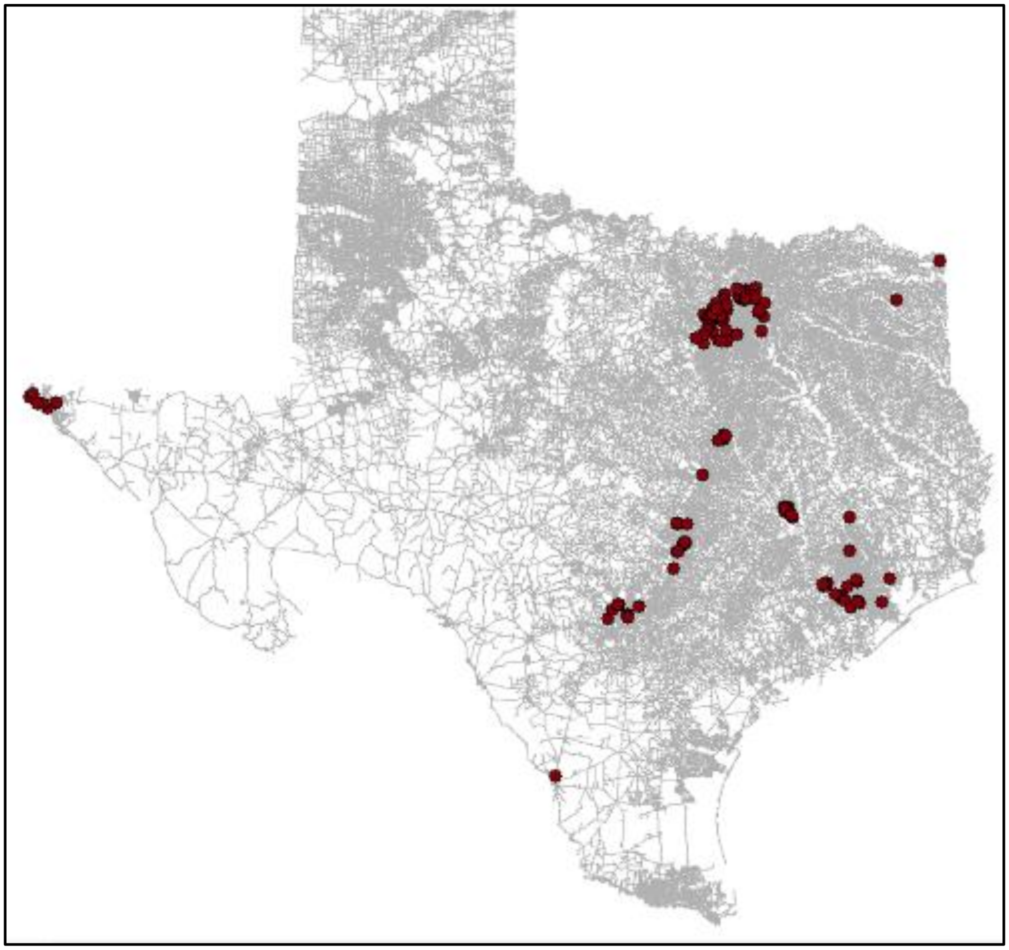


**Figure 33. Texas Roundabouts Identified in Online Inventory (*106*).**

**Table 7. Sample of Roundabout Intersections Identified in Task 2.**

| Intersection | District | City | Legs | Rural? | PSL? | Trucks? |
|---|---|---|---|---|---|---|
| E 51st St/I-35 SB Ramps | AUS | Austin | 3 | No | Yes | — |
| FM 1375 Rd./I-45 SB Frontage Rd. | BRY | New Waverly | 4 | Yes | Yes | — |
| FM 1375 Rd./I-45 NB Frontage Rd. | BRY | New Waverly | 4 | Yes | Yes | — |
| E. Paisano Dr./Alameda Ave. (West) | ELP | El Paso | 3 | Maybe | No | Maybe (6–19%) |
| E. Paisano Dr./Alameda Ave. (East) | ELP | El Paso | 4 | Maybe | No | Maybe (6–19%) |
| Harmon Rd./US 81-US 287 SB Frontage Road | FTW | Fort Worth | 3 | No | Yes | — |
| Harmon Rd./US 81-US 287 NB Frontage Road | FTW | Fort Worth | 4 | No | Yes | — |
| Cane Island Pkwy./Commerce Pkwy./Parkside St. | HOU | Katy | 4 | Yes | No | — |
| Tamarron Pkwy./Tamarron Trace | HOU | Katy | 4 | No | Yes | — |
| Sienna Pkwy./Mount Logan | HOU | Missouri City | 4 | No | Yes | — |
| Waco Traffic Circle (US 77/Circle Rd./S Valley Mills Dr./La Salle Ave./N Robinson Dr.) | WAC | Waco | 5 | No | No | Maybe (6–17%) |
| Chapel Rd./Ritchie Rd. | WAC | Waco | 4 | Yes | No | — |
| San Pedro Ave./N Main Ave./Navarro St. | SAN | San Antonio | 3 | No | No | Maybe (10%) |

*Note: — = unknown. Rural = Is the intersection in a rural (or suburban) area? PSL = Does at least one approach have a posted speed limit of at least 45 mph? Trucks = Does the intersection serve a high estimated truck percentage at the intersection, and/or does it serve OSOW vehicles?*

## IDENTIFICATION OF STUDY SITES

The research team used the information from the Task 2 efforts as a starting point for identifying and selecting study sites in the Task 6 field studies.

### Sites in Texas

Ultimately the research team compiled information on all 189 sites shown in Figure 33, including the number of approaching roadway legs, number of driveways, number of lanes, and the year in which the roundabout was completed, along with viability notes for the sites with the greatest potential to be study sites. The vast majority of the 189 sites identified in the search did not contain most of the necessary characteristics, if any. That is, most sites were typically located in urbanized areas with speeds of 40 mph or lower, and/or they did not serve substantial truck volumes or have any reliable indicators of truck volumes. Ultimately, the sites summarized in

Table 7 represented the most suitable sites within the state. With that information in hand, the research team determined that the sites with the best potential for use as study sites were the Cane Island Parkway site in Katy and the roundabout diamond interchange on I-45 in New Waverly.

*Cane Island Parkway at Commerce Parkway/Parkside Street (Katy)*

The intersection at the Katy study site (see Figure 34) is in a suburban environment and consists of four legs, each one an arterial or collector not on the state highway system; however, the intersection itself is approximately 0.1 mile north of the westbound frontage road for the I-10 Katy Freeway, so much of the traffic that passes through the intersection comes from or is going to the freeway. Each approach to the intersection has two travel lanes, as does the roundabout's circulating roadway and each departure leg. The speed limit on each leg is either 30 or 35 mph, but the site was chosen for its truck volumes (estimated at 3.2 percent of ADT) because of its proximity to large distribution centers and industrial development on the streets to the north and west of the intersection. The northeast corner of the intersection contains a national chain pharmacy, and development on the southeast corner consists of a large Texas-based fuel and travel center. The southwest corner of the intersection is undeveloped.

The research team selected this site as a study site to collect data on speeds, traffic volumes, and other traffic characteristics. A description of the data collection activities and a summary of the data are provided in a subsequent section of this chapter.

Source: Base image from Google Earth.
**Figure 34. Aerial View of Katy Study Site.**

*I-45 at FM 1375 (New Waverly)*

The study site in New Waverly is in a generally rural environment and consists of two intersections, one on either side of the I-45 freeway at its diamond interchange with FM 1375 (see Figure 35). The north and south legs of each roundabout intersection are two-way frontage roads serving I-45, with the east-west rural arterial FM 1375 connecting the two intersections under I-45. All of the approaches have one travel lane in each direction. The posted speed limit on the frontage roads is 45 mph; FM 1375 has a posted speed limit of 50 mph on the east side of the freeway into New Waverly and 60 mph on the west side of the freeway outside of the city limits. The proportion of trucks in the daily traffic volume is estimated between 3 and 5 percent, reflective of its proximity to the freeway as well as regional traffic using FM 1375. The land adjacent to both intersections is generally undeveloped.

The research team initially selected this site as a second study site for data collection based on its favorable characteristics of rural location, high-speed approaches, and truck traffic. However, the timeline of a project to reconstruct I-45 through the area coincided with the available data collection window, substantially altering traffic volumes and patterns through the area during the construction period. As a result, researchers were unable to collect data at this site during the project.


Source: Base image from Google Earth.

**Figure 35. Aerial View of New Waverly Study Site.**

## Sites in Other States

Given the low number of available sites in Texas that had the desired characteristics for this project presented in Task 2, members of the Receiving Agency Project Team recommended at the project kickoff meeting that the research team consider looking at locations outside the state.

As part of their review of current practices in Task 2, researchers reached out to practitioners in other states to ask about their experiences with roundabouts in high-speed locations that serve trucks. While the primary purpose of that effort was to learn about existing guidance on design, installation, and operation of such roundabouts, along with findings from relevant research, it also provided an opportunity to ask those practitioners about locations where such roundabouts were in operation. Researchers followed up with those practitioners who indicated they knew of locations that had roundabouts with one or more of the desired characteristics. Responses to those follow-up discussions returned 39 intersections in 13 states:

- Arizona (1 site).
- Florida (1).
- Georgia (1).
- Indiana (1).
- Kansas (8).
- Michigan (5).
- Missouri (3).
- North Carolina (5).
- New Hampshire (1).
- New York (2).
- Ohio (2).
- Washington (4).
- Wisconsin (5).

Researchers used these suggestions to explore options for suitable out-of-state study sites. In their review of the sites, researchers emphasized consideration of multiple sites in relative proximity, states where the corresponding road agency could provide support with background information and help obtain any necessary approvals to collect data, and coordination with the parallel Task 7 data collection effort at innovative intersections, as appropriate. With that in mind, researchers focused first on states with more than one site, then on locations within those states that had multiple sites. That led the research team to consider clusters of sites in three states, as shown in Table 8.

**Table 8. Potential Out-of-State Study Sites.**

| State | City | Intersection | Legs | Rural? | PSL? | Trucks? |
|---|---|---|---|---|---|---|
| KS | Florence | US-50 at US-77 | 5 | Yes | Yes | 50% |
| KS | Marion | US-77 at US-56 | 4 | Yes | Yes | 35% |
| KS | Paola | Kansas Highway 68 at Old KC Road | 5 | Yes | Yes | 20% |
| KS | Garnett | N. Jct. US-59 and US-169 | 3 | Yes | Yes | 20% |
| KS | Arkansas City | US-77 at US-166 | 4 | Yes | Yes | 15% |
| KS | Fredonia | US-400 at Kansas Highway 47/Washington Street | 4 | Yes | Yes | 20% |
| KS | Riverton | US-400 at US-66 | 4 | Yes | Yes | 15% |
| KS | Lyndon | US-75 at Kansas Highways 31/268 | 4 | Yes | Yes | 10% |
| MO | Belton | I-49/US-71 Northbound Frontage Road at E. 155th Street | 6 | Yes | Yes | — |
| MO | Warrensburg | State Route 13 and Business Route 13 at NW 435th Road | 4 | Yes | Yes | — |
| MO | Warrensburg | State Route 13 and Business Route 13 at SE 101st Road | 4 | Yes | Yes | — |
| NC | New Salem | NC 218 at NC 205 | 4 | Yes | Yes | — |
| NC | Monroe | NC 75 at Rocky River Road/Old Waxhaw-Monroe Road | 4 | Yes | Yes | — |
| NC | Laurinburg | US-15/US-501 at NC 144 | 4 | Yes | Yes | — |
| NC | Shelby | Lafayette Street at Zion Church Road | 4 | Yes | Yes | — |
| NC | Mulberry | Yellowbanks Road at Haymeadow Road | 4 | Yes | Yes | — |

*Note: — = unknown. Rural = Is the intersection in a rural (or suburban) area? PSL = Does at least one approach have a posted speed limit of at least 45 mph? Trucks = What is the estimated truck percentage at the intersection?*

Based on the information available and the proximity of the listed sites, the research team decided to proceed with investigating sites in Kansas. They obtained additional information from contacts at KDOT and compiled details for discussion with the Receiving Agency. In that discussion, researchers presented the eight Kansas sites and relative benefits and features of each site to the Receiving Agency. After the sites were presented, the Receiving Agency indicated a preference for four-leg intersections to provide a basis for the subsequent simulation scenarios that better reflected the likely configuration that would be found on the state highway system. The Receiving Agency also stated that a truck percentage of at least 10 percent was sufficient for obtaining the desired amount of truck traffic data for the simulation. The characteristics of each site led to a stated preference for the Lyndon site, along with one additional site among the cluster of Arkansas City, Fredonia, and Riverton in the southeast quadrant of the state. With that guidance from the Receiving Agency, researchers selected the Fredonia site as the second Kansas site for data collection along with the Lyndon site.

The Lyndon site (shown in Figure 36) is in a rural environment approximately 1 mile north of the city limits of Lyndon in east-central Kansas, about 20 miles south of the city of Topeka. The major road is US-75, which is a regional north-south rural arterial. The east leg of the intersection is Kansas Highway 268 (K-268), and the west leg is K-31. Each of these highways has one travel lane in each direction, and the circulating roadway at the roundabout (built in 2014) also has one lane. The posted speed limit on the north and east legs is 65 mph, and the limit on the south and west legs is 55 mph. KDOT traffic counts indicate an ADT of 8,800 vehicles per day with 11 percent trucks. The area around the intersection is undeveloped, though there is a small parking area for regional park-and-ride users near the southeast corner.

The Fredonia site (shown in Figure 37) is in a generally rural environment, just outside the city limits of Fredonia in southeast Kansas, approximately 80 miles east of the city of Wichita. The north-south road, US-400, is the major road. The east leg of the intersection is K-47, while the west leg of the intersection leads into Fredonia and is labeled as Washington Street, a minor arterial not on the state highway system. Each of these roads is a two-lane roadway, and the roundabout (built in 2009) has a single circulating lane. The posted speed limit is 65 mph on the three state highway legs; upon entering the city limits approximately 0.1 mile from the intersection, the posted speed limit on Washington Street is 30 mph. KDOT traffic counts show approximately 6,200 vehicles per day entering the intersection, about 20 percent of which are heavy vehicles. The property at the southeast corner of the intersection contains a truck stop with a convenience store and restaurants, with the sole access point about 0.1 mile east of the intersection on K-47. The remaining adjacent land is generally undeveloped, though low-density single-family residential development can be found nearby on Washington Street.


Source: Base image from Google Earth.
**Figure 36. Aerial View of Lyndon Study Site.**


Source: Base image from Google Earth.

**Figure 37. Aerial View of Fredonia Study Site.**

## FIELD DATA COLLECTION

The research team used two methods for collecting field data at the study sites, one method for in-state data collection and a second method for out-of-state data collection. Initially, the research team planned to use a similar approach for all sites; however, a number of factors combined to make it worthwhile to conduct the out-of-state data collection in a different manner. First, the research team used the in-state data collection as a means of learning about the capabilities of the equipment traditionally used to collect similar data at conventional intersections and found opportunities for improvement and efficiencies in revising the data collection approach. Second, improvements in technology allowed the research team to consider new methods of data collection and reduction not previously available or feasible. Third, while the research team had conducted out-of-state data collection on numerous projects in the past, arranging for the necessary equipment and personnel to travel to out-of-state locations introduced an additional level of complexity and expense, which was compounded by restrictions related to COVID-19 that arose after Task 6 began. All of these factors led the research team, with concurrence from the Receiving Agency, to partner with a third-party vendor to collect and initially reduce the data from the Kansas sites. Details of both data collection methods, for in-state and out-of-state sites, are provided in the following sections.

**Katy, Texas**

As described previously, due to the limited number of viable study sites in Texas, this site was chosen as the best option available for Texas data collection. While plans were still ongoing for finding potential study sites elsewhere in Texas (and eventually in Kansas), the purpose of this initial data collection was to collect useful roundabout data as well as to verify and test data collection methodologies and techniques being used to record the necessary data for the upcoming simulation effort. The effort at this site focused on traditional data collection methods and employed multiple methods to obtain the desired data for speeds, volumes, and turning movement counts. Primarily, the team deployed ground-based traffic video recording devices to record video of traffic approaching, entering, and circulating the roundabout. Specifically, the team deployed a solar-powered video recording trailer with an extendable, telescoping mast. The trailer was parked in a private parking lot on the southeast corner of the roundabout, and the cameras were approximately 25 feet off the ground. Figure 38 shows an aerial overview of the roundabout and the location of the data collection trailer.


Source: Base image from Google Maps.
**Figure 38. Annotated Aerial Image of Katy, TX, Data Collection Site.**

Traffic video was recorded continuously (day and night) for multiple weekdays. Due to the field of vision available at the trailer location, two cameras were used to record the entire roundabout. Figure 39 shows the recorded video images for both cameras.


**Figure 39. Camera View for Trailer Video at Katy, TX, Data Collection Site**

The main purpose of this video recording was to obtain vehicle turning movement counts (i.e., origin-destination counts). Research staff reduced the video for the peak periods from one day, and these counts are shown in Table 9 and Table 10.

**Table 9. Vehicle Turning Movement Count for Cane Island Parkway at Commerce Pkwy/Parkside St (August 20, 2020).**

| Time Begin | Northbound Cane Island Pkwy | | | | Southbound Cane Island Pkwy | | | | Eastbound Commerce Pkwy | | | | Westbound Parkside St | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | U-Turn | Left | Thru | Right | U-Turn | Left | Thru | Right | U-Turn | Left | Thru | Right | U-Turn | Left | Thru | Right |
| 7–8 AM | 265 | 73 | 150 | 87 | 0 | 38 | 184 | 4 | 0 | 0 | 1 | 16 | 0 | 155 | 17 | 60 |
| 8–9 AM | 268 | 106 | 124 | 111 | 0 | 32 | 141 | 8 | 0 | 3 | 12 | 32 | 0 | 202 | 17 | 42 |
| 11–12 PM | 207 | 56 | 146 | 132 | 2 | 39 | 210 | 14 | 0 | 4 | 62 | 144 | 0 | 263 | 28 | 64 |
| 12–1 PM | 266 | 37 | 122 | 156 | 0 | 32 | 171 | 10 | 0 | 8 | 23 | 90 | 0 | 245 | 17 | 65 |
| 4–5 PM | 367 | 72 | 148 | 129 | 0 | 11 | 223 | 19 | 0 | 4 | 35 | 97 | 0 | 180 | 34 | 83 |
| 5–6 PM | 393 | 67 | 161 | 116 | 1 | 11 | 206 | 14 | 1 | 10 | 41 | 146 | 0 | 206 | 63 | 64 |

**Table 10. Heavy Vehicle Percentages from Vehicle Turning Movement Count for Cane Island Parkway at Commerce Pkwy/Parkside St (August 20, 2020).**

| Time Begin | Northbound Cane Island Pkwy | | | | Southbound Cane Island Pkwy | | | | Eastbound Commerce Pkwy | | | | Westbound Parkside St | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | U-Turn | Left | Thru | Right | U-Turn | Left | Thru | Right | U-Turn | Left | Thru | Right | U-Turn | Left | Thru | Right |
| 7–8 AM | 2 | 7 | 14 | 1 | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 19 | 0 | 1 | 0 | 2 |
| 8–9 AM | 2 | 4 | 11 | 2 | 0 | 0 | 13 | 0 | 0 | 0 | 0 | 16 | 0 | 0 | 6 | 0 |
| 11–12 PM | 2 | 11 | 16 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 0 | 2 |
| 12–1 PM | 2 | 8 | 12 | 1 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 3 |
| 4–5 PM | 0 | 0 | 7 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |
| 5–6 PM | 1 | 4 | 2 | 3 | 0 | 0 | 1 | 7 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 |

This dataset confirmed that this site has moderate to high traffic volume demand and that there are substantial proportions of heavy vehicles that use this roundabout, with several hours having more than 10 percent trucks on certain movements.

Research staff deployed automatic traffic recorders (e.g., tube counters) on all approaches to this roundabout to collect approach speed data, and they used the raw data setup to record vehicle classifications and speeds. This data collection revealed some limitations in the use of this equipment at this site. One purpose of this data collection method was to collect approach speeds far upstream and immediately upstream of the flare on each approach to the roundabout. As described previously, the site is near a major gas station and retail outlet (on the southeast corner), with a major online retailer warehouse a short distance to the west and a freeway overpass on the south side (which feeds the northbound approach to the roundabout). Each of these features is directly related to one or more access points near the roundabout and provides heavy vehicle traffic using those access points. The proximity of these access points made it difficult to place the counters as far upstream as originally planned to collect approach speed data, so the counters were placed slightly closer to the roundabout. The near-upstream traffic counters were deployed between 200 and 300 feet upstream of the roundabout entrance on each approach, and the far-upstream traffic counters were deployed between 700 and 800 feet upstream of the roundabout entrance on each approach.

During the data collection period, the data collection team had difficulty keeping the tubes secured, and they noted many vehicles making hard turns and lane changes near the data collection points. While a great deal of effort was made to keep the equipment working during the data collection period, the resulting data was limited and lacking in the accuracy needed for the study. The data issues seemed to stem from the busy access points along three approaches as well as the fact that the data collection devices were deployed closer to the roundabout than originally planned. Based on a review of the data and conditions at the site, it is likely that the decelerations of vehicles on the approaches led to both imprecise (or inaccurate) speed measurements as well as equipment failures because road tubes were damaged or dislodged. Thus, the data obtained from this portion of the data collection effort had limited usefulness and was not reduced further.

The research team also used another data collection method (specifically, a lidar speed measurement gun) to record speeds during the same August 2020 data collection period described for the video and traffic counter data collection efforts mentioned previously. One positive feature with the lidar gun data collection method, and a primary reason why the research team chose to use it, was that it could provide detailed speed profiles of vehicles decelerating on the approaches. The intended plan called for the data collection team to record many measurements of vehicles approaching the roundabout with the lidar guns, compiling a speed profile of each approaching vehicle from several hundred feet upstream all the way up to the roundabout entrance yield point; however, this proved to be particularly difficult to achieve. The proximity of the previously mentioned access points and the frequent deceleration and lane-changing behavior on the near approach to the roundabout led to occlusion problems for the data collection team (particularly with frequent heavy vehicles), which negatively affected the ability to manually track the decelerating vehicles (i.e., keep the lidar beam fixed on the vehicle as it slowed). As a result, the lidar gun effort produced a very limited data set of speed profiles and valid speeds on which to base a simulation model.

Finally, the team deployed additional ground-based traffic video recording devices to record video of traffic as it entered the roundabout. These were portable video recorders with telescoping pole-mounted cameras, and they were deployed in the central island. The intent of this data collection was to record close-up videos of each roundabout entrance point merge area and reduce the video in greater detail to extract gap data (i.e., gaps in traffic accepted and rejected by entering vehicles). Figure 40 shows an example of the recorded video image for the westbound approach.


**Figure 40. Camera View for Portable Video Recorder at Katy, TX, Data Collection Site.**

Once the video was recorded, researchers reviewed the video and devised a process to extract the gap acceptance data for entering vehicles. Researchers reduced a small portion of the video to determine the efficacy of the process, and the results from that sample made it clear to the research team that this video reduction process was slow and labor-intensive for the type and quantity of data that were desired for the project. Based on these findings, researchers began to emphasize the investigation of alternate methods of data collection and reduction for the field data.

In summary, this initial data collection effort provided some useful data, but much of the data necessary for the simulation modeling work was either very difficult to collect, or, at best, were collected with methods that were both exhausting in process and resulted in a lower accuracy than desired for the planned modeling effort. The fact that this site was a two-lane roundabout added to the complexity of collecting data using these methods; the multiple lanes on this roundabout and its approaches introduced lane-changing activity not seen at single-lane sites, as well as greater chance for occlusion from video or lidar lines of sight, compounded by the high truck percentages in the approach volumes. As a result, many of the traditional data collection methods used at this site were ultimately pushed past their limitations. Therefore, when developing the plans for data collection at additional sites, the research team sought out an entirely different and non-traditional approach for collecting and subsequently reducing that dataset.

### Lyndon and Fredonia, Kansas

While the research team was able to collect some meaningful data at the Katy site, it became apparent that the methods and materials used for that data collection were relatively labor-intensive and required many pieces of equipment, while still leaving room for improvement. The research team recognized that improvements in technology provided new tools with the potential to collect the data much more thoroughly and simply while reducing the amount of equipment and the amount of personnel time needed to obtain the data. Researchers during the proposal process and subsequently in the project kickoff meeting raised the option of using unmanned aerial vehicles (UAVs, commonly called “drones”) to record traffic activity at roundabout study sites. Other research efforts to study and monitor activities at roundabouts have used drones to collect data and have shown that they have a unique ability to capture images from the entire intersection, providing a means of not only obtaining traffic volumes but following the path of each vehicle as it enters and exits to generate turning movement counts as well as the vantage point needed to observe any unusual behaviors, gap acceptance trends, usage of the truck apron, and other features all from a single camera.

While the research team did not have the ability in-house in Task 6 to collect the data using drones, a variety of third-party vendors did have this capability and specialized in this type of service. In addition, improvements in machine-vision technology have greatly improved the capability to automate data reduction for traffic data collected from video using computer software instead of manual review and reduction, and many of the aforementioned vendors also had access to such software. The combination of these improvements in drone and software capability and availability suggested that using drones to collect the data would be more efficient and provide better data. These factors, combined with restrictions on research team travel related to COVID-19 that developed during Task 6, made it even more suitable for a third-party vendor to collect the Kansas data using drones and initially reduce the data using computer algorithms.

With the concurrence of the Receiving Agency, researchers selected a vendor through a standard bidding process to complete those activities.

The selected vendor visited each site on multiple days in January 2021 to collect data on both a weekend day and a weekday; data collection occurred at Fredonia on January 9 and 14 and at Lyndon on January 10 and 13, and all videos were recorded during daylight hours, approximately between 7:45 a.m. and 6:15 p.m. While at each site, the vendor identified a suitable location in the central island of the roundabout to set up the necessary equipment and then raised the drone from the center of the island to a height of approximately 400 ft where the drone recorded video for the duration of its battery life (approximately 30 minutes). As the drone neared the end of its battery life, the vendor landed the drone in the central island, replaced the battery, and then raised the drone back to its previous elevated position to continue recording video footage. When both batteries were exhausted, the vendor recharged the batteries and then began recording again. The vendor used a flight planning software application to ensure that the video was captured from the same geolocational position (Longitude X, Latitude Y, Altitude Z) with the same field of view from the camera for each recording. In total, the vendor collected more than 6 hours of video from each site, as summarized in Table 11.

**Table 11. Summary of Video Data Collection Periods at Kansas Sites.**

| **Fredonia Site** | | | **Lyndon Site** | | |
|---|---|---|---|---|---|
| **Date** | **Time** | **Duration** | **Date** | **Time** | **Duration** |
| January 9 | 9:25 AM | 29:01 | January 10 | 11:53 AM | 29:01 |
| | 10:04 AM | 29:00 | | 12:30 PM | 30:47 |
| | 11:49 AM | 32:09 | | 1:07 PM | 29:01 |
| | 12:27 AM | 33:19 | | 1:53 PM | 29:45 |
| | 2:37 PM | 29:01 | | 3:00 PM | 33:01 |
| | 3:14 PM | 31:21 | | 3:39 PM | 25:19 |
| | 3:54 PM | 32:12 | January 13 | 7:50 AM | 31:57 |
| January 14 | 12:47 PM | 20:01 | | 8:27 AM | 28:32 |
| | 1:11 PM | 27:04 | | 11:35 AM | 33:54 |
| | 2:45 PM | 20:01 | | 12:21 PM | 30:52 |
| | 2:58 PM | 25:01 | | 4:25 PM | 31:52 |
| | 4:28 PM | 22:52 | | 5:01 PM | 25:32 |
| | 4:59 PM | 28:11 | | 5:30 PM | 17:06 |
| | 5:32 PM | 18:42 | | | |
| Total | | 6:17:55 | Total | | 6:16:38 |

After recording the video footage, the vendor processed the collected images using commercial grade traffic analysis software (i.e., Data From Sky) that featured tracking algorithms that captured detailed vehicle and trajectory information. The software focused on three vehicle types: cars (i.e., typical passenger vehicles), medium vehicles (corresponding to the European classification of Ordinary Goods Vehicle 1, which is equivalent to most box trucks and delivery vans), and heavy vehicles (which includes tractor-trailers, buses, and similar vehicles).

Figure 41 shows real-time vehicle and trajectory information tagged by the software for a portion of the footage (January 13, 2021, 4:00 p.m. hour) from the roundabout in Lyndon. The highlighted heavy vehicle on the east leg (ID 401) is shown with its associated travel path displayed; the lime-colored line east of the vehicle indicates the finished track, and the teal line west of the vehicle indicates the track yet to follow.

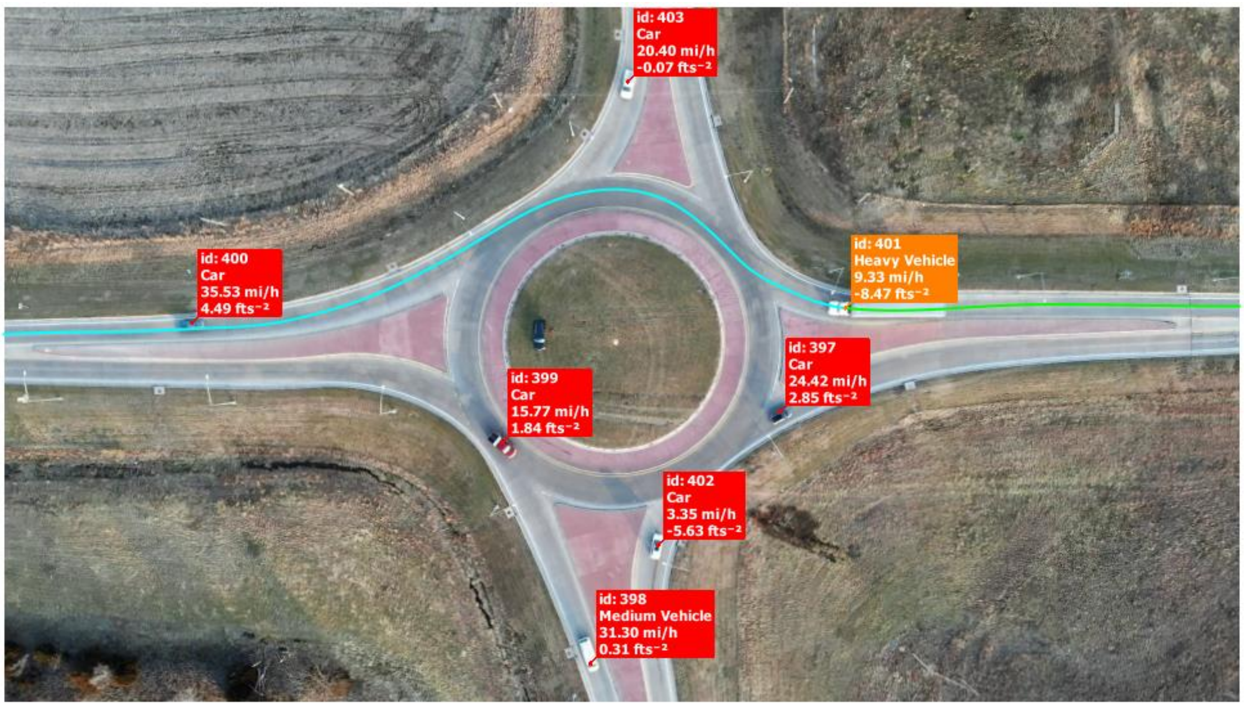



**Figure 41. Vehicle and Trajectory Information Extracted from Aerial Drone Footage.**

The software defined various cross-section locations in a roundabout as gates and assigned an ID to each gate. These gate locations include approach upstream, approach at yield line, neutral gate, and departure at yield line at each leg of the roundabout. Figure 42 shows the locations of these gates for the west leg of the roundabout in Fredonia, Kansas.

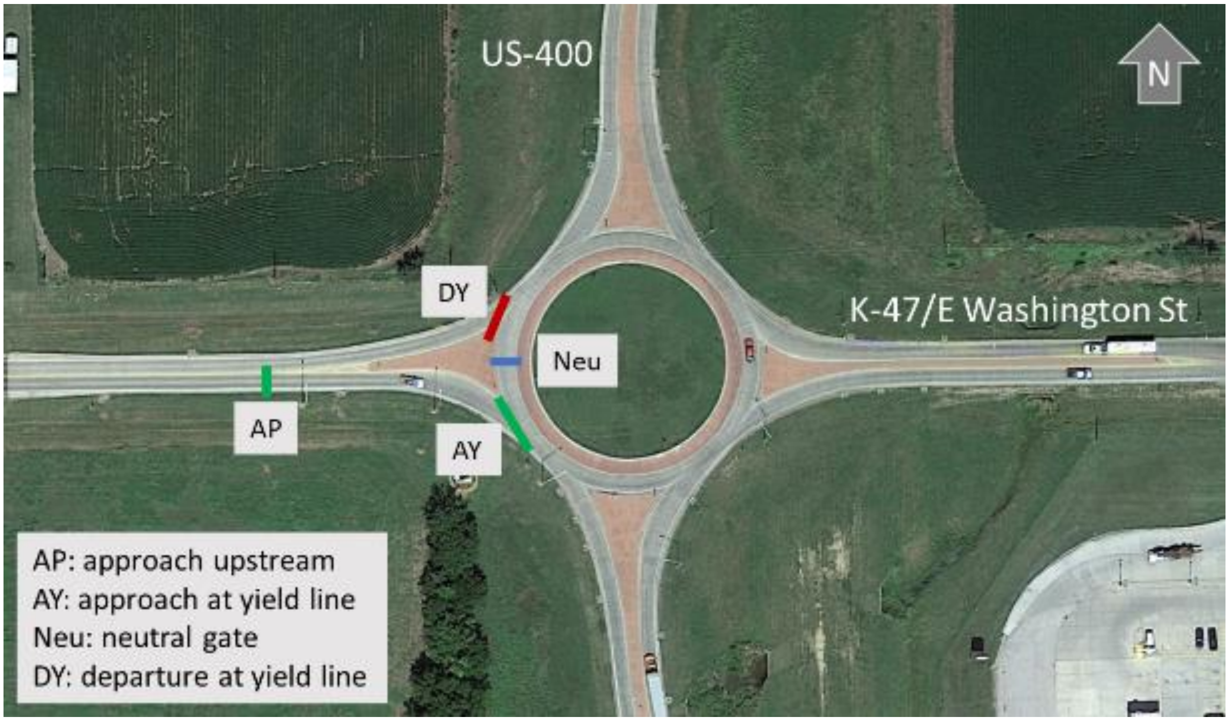



**Figure 42. Gate Definition for Roundabout Data Collection.**

The software used these gate locations as the reference points to process the trajectory information to identify movements or events (e.g., a stationary or yielding event). The compiled information was then stored in various output data files in comma-separated values format. Table 12 is a list of the generated output data files and their respective contents.

**Table 12. Drone Data Collection Output Files.**

| Output File | File Data Content |
|---|---|
| Trajectory | Site name, vehicle ID and type, entry and exit gate and time stamp, traveled distance (ft), average speed (mph). |
| Trajectory Movement | Site name; vehicle ID and type; passed gates; distance between gates (ft); total traveled distance (ft) and time (sec); statistics of: speed (mph), acceleration (ft/s$^2$), lateral acceleration (ft/s$^2$), and tangential acceleration (ft/s$^2$); total and longest stationary time (sec). |
| Stationary | Site name, vehicle ID and type, start or end time of a stationary event. |
| Gate Cross | Site name, vehicle ID and type, crossed gate ID and time stamp, tangential/lateral acceleration, temporary and spatial headway (sec). |
| Apron Encroachment Event | Site name, encroaching vehicle ID and type, time stamp and footage ID, speed (mph), tangential and lateral acceleration (ft/s$^2$), temporary and spatial headway (sec). |

| | |
|---|---|
| Traffic Analysis Overview | Site name, number of vehicles by type, total distance travel (ft), average speed (mph). |
| Traffic Analysis by Gate | Site name, gate ID, statistics of speed (mph), number of vehicles by type, total number of vehicles. |
| Traffic Analysis by Turns | Site name, number of vehicles coming from an entry or approach gate to difference exit gates. |
| Gap Time | Site name, waiting event ID, waited gate, video position of first blocking (msec), first (and second) blocking vehicle ID, first waiting vehicle ID, number of waiting vehicles, gap time (msec), first left waiting vehicle ID, number of left waiting vehicles, entered vehicle count, reaction time, following entered vehicle ID, video position of following vehicle entry (msec). |
| Origin-Destination (OD) Data | Site name, entry or approach gate ID, exit gate ID, number of vehicles coming from an entry or approach gate to an exit gate. |
| Time to Collision | Site name, ID and type of involved vehicles, time to collision (sec), coordinates of the conflict, angle of involved vehicles. |
| Approach Gate Data | Site name, crossing vehicle ID and type, time, speed, tangential and lateral acceleration ($ft/s^2$), temporary and spatial headway (sec). |

These data files contained extensive data that was useful for modeling the roundabouts in Kansas. The research team processed the data from these files to produce summaries from the data collection periods, beginning with traffic volumes. Table 13 shows the summary of the equivalent total hourly demand collected from the two roundabouts in Kansas.

**Table 13. Hourly Traffic Demand at the Kansas Roundabout Sites.**

| **Site** | **Day of Week** | **Vehicle Type** | | | **Heavy Vehicles Percent (%)** | **Total Vehicles** |
|---|---|---|---|---|---|---|
| | | **Car** | **Medium** | **Heavy** | | |
| | | (Min, Max) | (Min, Max) | (Min, Max) | (Min, Max) | (Min, Max) |
| Fredonia | Weekend | (293, 420) | (2, 18) | (21, 41) | (6.5, 9.9) | (321, 478) |
| | Weekday | (272, 435) | (8, 53) | (36, 56) | (9.4, 11.6) | (317, 502) |
| Lyndon | Weekend | (391, 470) | (0, 9) | (10, 23) | (2.3, 5.1) | (407, 486) |
| | Weekday | (360, 623) | (4, 29) | (28, 95) | (4.3, 18.1) | (429, 657) |

The research team processed the Trajectory Movement datasets to obtain the average speed and travel time between gates. Table 14 lists the summarized OD travel times for the two roundabouts in Kansas.

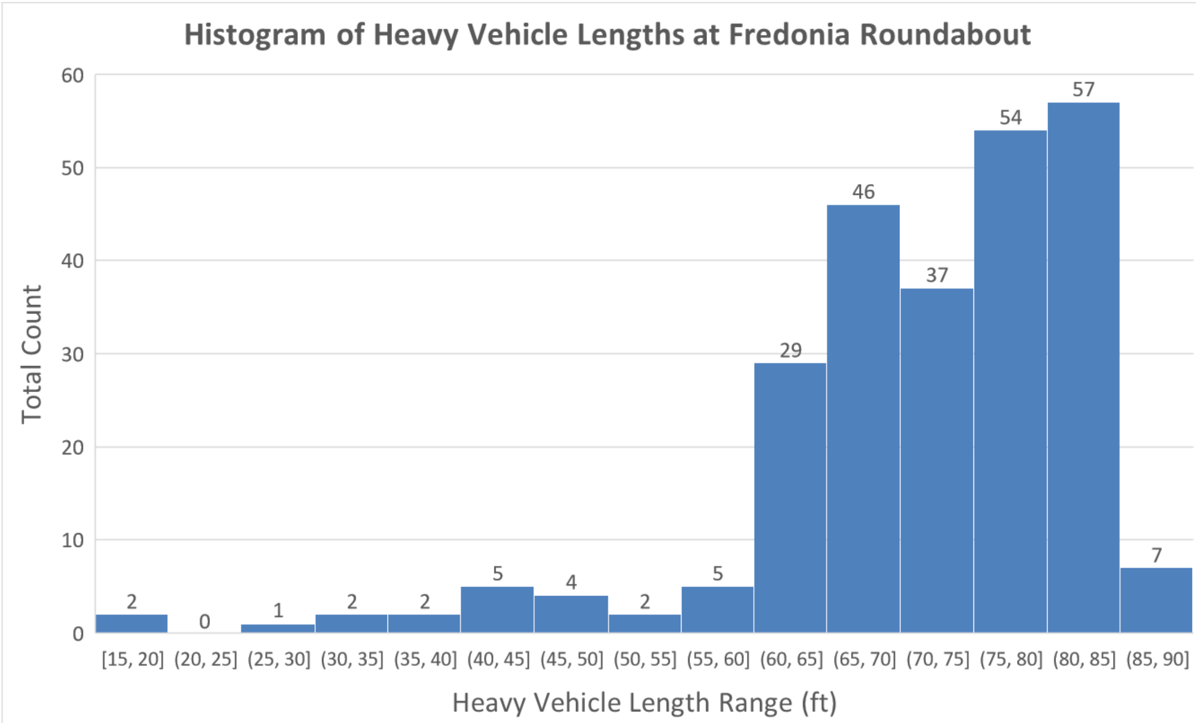
**Table 14. Average Travel Times (sec) for Various OD Pairs.**

| Site | Vehicle Type | WB LT | WB RT | NB LT | EB LT | EB TH | SB LT |
|---|---|---|---|---|---|---|---|
| Fredonia | Car | 21.1 | 9.7 | 26.0 | 20.9 | 14.6 | 25.6 |
| | Medium | 28.7 | 12.4 | 23.8 | NA | 16.4 | 33.3 |
| | Heavy | 19.9 | 9.2 | 27.8 | 24.4 | 14.3 | 28.6 |
| | All | 22.1 | 10.0 | 26.1 | 21.1 | 14.6 | 26.8 |
| Lyndon | Car | 7.9 | 17.9 | 23.6 | 15.4 | 20.6 | 22.5 |
| | Medium | 6.6 | 22.9 | 30.0 | 20.0 | 22.9 | 29.0 |
| | Heavy | 13.4 | 20.4 | 20.1 | 15.8 | N/A | N/A |
| | All | 8.0 | 18.2 | 23.7 | 15.6 | 20.6 | 22.9 |

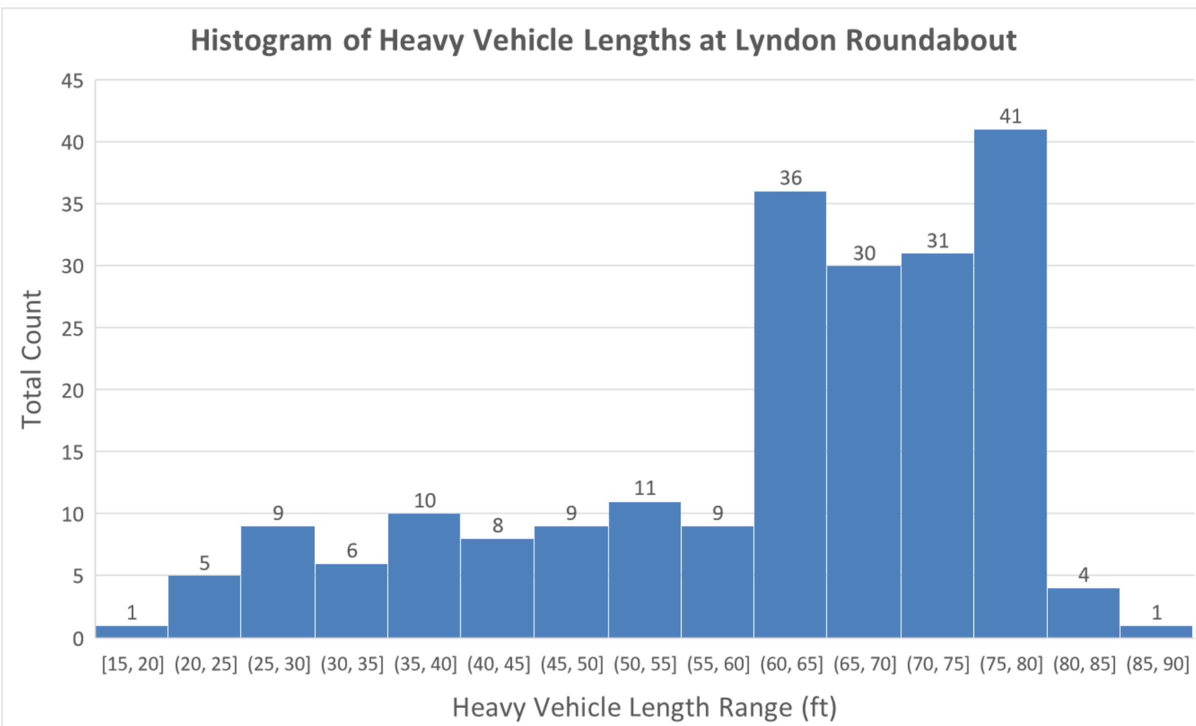
*Note: N/A = not applicable.*

Despite the detailed data output, the datasets did not include two pieces of information, a count of OSOW vehicles and the free-flow speed for all vehicle types, that were needed for simulation modeling and evaluating roundabouts in this research. Thus, the research team designed procedures to further reduce the drone data for extracting such information.

To identify OSOW vehicles, the research team processed the aerial footage to measure the size of heavy vehicles (known from available vehicle type information). A total of 483 heavy vehicles were identified from the Gate Cross data file. Figure 43 provides histograms of the vehicle lengths.




a) Fredonia Roundabout




b) Lyndon Roundabout

**Figure 43. Histograms of Heavy Vehicle Lengths at Kansas Roundabouts.**

Vehicles can be classified as OSOW by three criteria: weight, width, and length. As noted in the previous figures, the processed field data yielded a dataset of recorded vehicle lengths. Vehicle weights and widths were not included in the collected field data; therefore, the research team relied on vehicle length measurements as the sole measure for determining OSOW vehicles. While there is not a universal definition of what constitutes an OSOW vehicle, the research team consulted multiple sources on state permitting procedures and regulations to determine a reasonable length threshold for OSOW vehicles.

The researchers focused this search on the states of Texas and Kansas (i.e., states where field data collection took place). Texas limits the trailer portion of a tractor-trailer combination to 59 feet but imposes no limit on the tractor truck portion of the combination (*107*). Similarly, Kansas limits the trailer portion of a tractor-trailer combination to 59.5 feet and also imposes no limit on the tractor truck portion of the combination (*108*). Both states also limit tandem trailers to a length of 28.5 feet each.

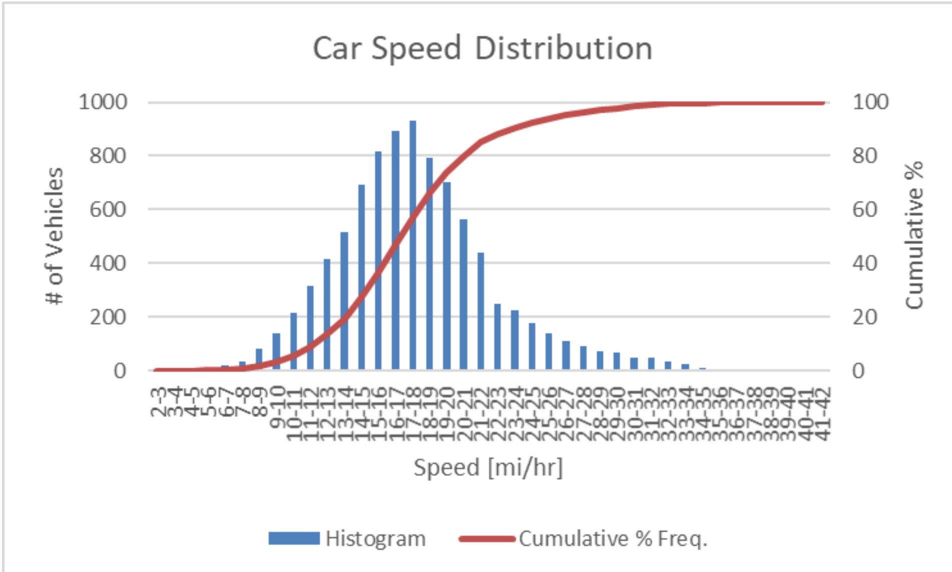
Thus, trucks pulling trailers exceeding those thresholds (69 feet in Texas and 69.5 feet in Kansas) would be considered OSOW and be required to adhere to the permitting regulations in the state(s) where the vehicle is to be operated. Unfortunately, the collected field data only included the length measurements of the truck-semitrailer combinations. So, the researchers found typical truck dimensions for the length from front bumper to the kingpin for multiple truck types and then accounted for the typical 3-ft trailer overhang. The length for a typical short-haul truck is 15.5 feet from front bumper to kingpin, so a truck-semitrailer combination guided by this truck would add 12.5 feet to the length of the trailer. Similarly, for typical long-haul trucks, they would add 13.5 feet and 20.5 feet for either the cabover or the conventional truck styles, respectively (*109*). Without a definitive source on the exact makeup of truck fleets, the researchers assumed an average of these three values of 12.5, 13.5, and 20.5 and determined a value of 15.5 feet for this added length. Combining this 15.5 feet with the maximum trailer length in Kansas (69.5 feet), the researchers settled upon a truck-semitrailer combination threshold of 85 feet for the purposes of defining OSOW vehicles in this research. Using that 85-ft threshold, researchers identified eight OSOW vehicles (comprising about 1.7 percent of truck traffic and about 0.1 percent of overall traffic) from the two roundabout sites in Kansas.

To identify the free-flow speed at the roundabouts, the research team cross-referenced the Stationary data file with the Gate Cross data file to exclude gating crossing speed samples associated with and affected by the stationary events. This was achieved by observing individual vehicles' driving behaviors in the aerial footages adjacent to the 182 stationary events. Vehicles slowing down or speeding up caused by the stationary events were marked for excluding their speed data points from the free flow speed sample set. Table 15 shows the number of free-flow speed samples filtered from the Gate Cross data file. The large number of free-flow samples is in accordance with the rural roundabout conditions where vehicle speeds are not often impeded due the relatively low traffic demand.

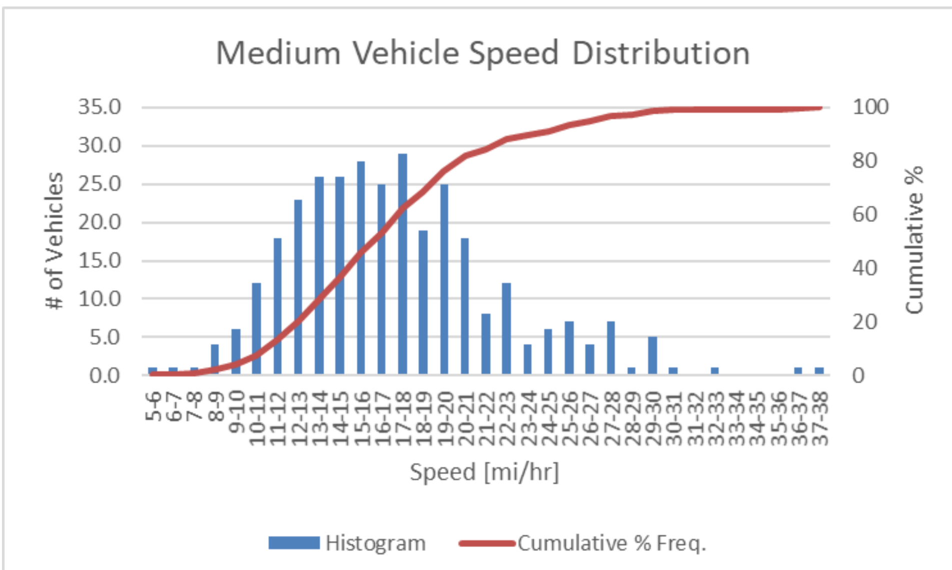
**Table 15. Number of Free-Flow Speed Samples Obtained from Drone Data.**

| Site Location | Vehicle Type | | | | Total |
|---|---|---|---|---|---|
| | Car | Medium | Heavy | OSOW | |
| Fredonia Site | 8906 | 320 | 1003 | 31 | 10233 |
| Lyndon Site | 9827 | 260 | 970 | 4 | 11061 |

These free-flow speed samples were used to generate desired speed distributions of individual vehicle types for simulating the traffic flows within the roundabout. Figure 44 and Figure 45 show the free-flow speed distributions of all four types of vehicles when circulating inside the roundabout in Fredonia.

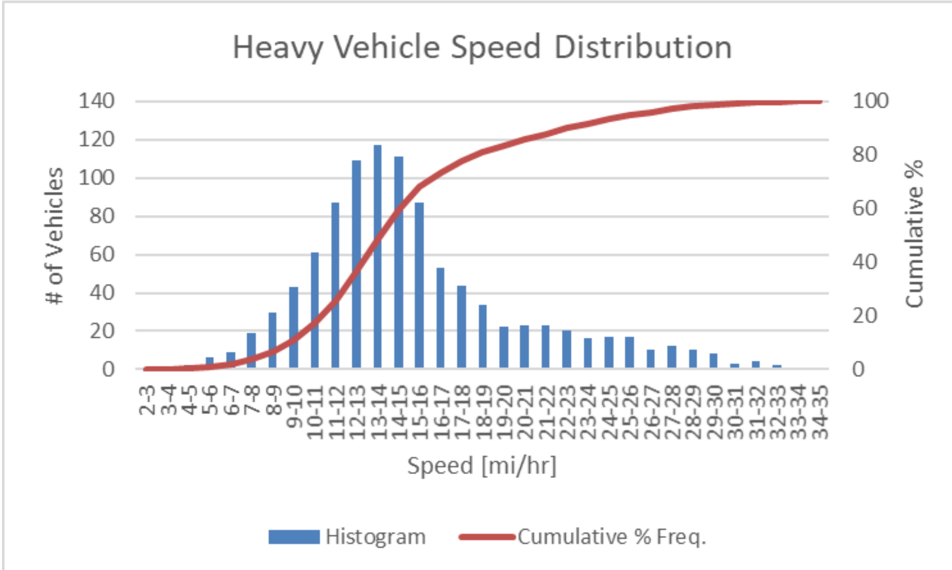



a) Passenger Cars

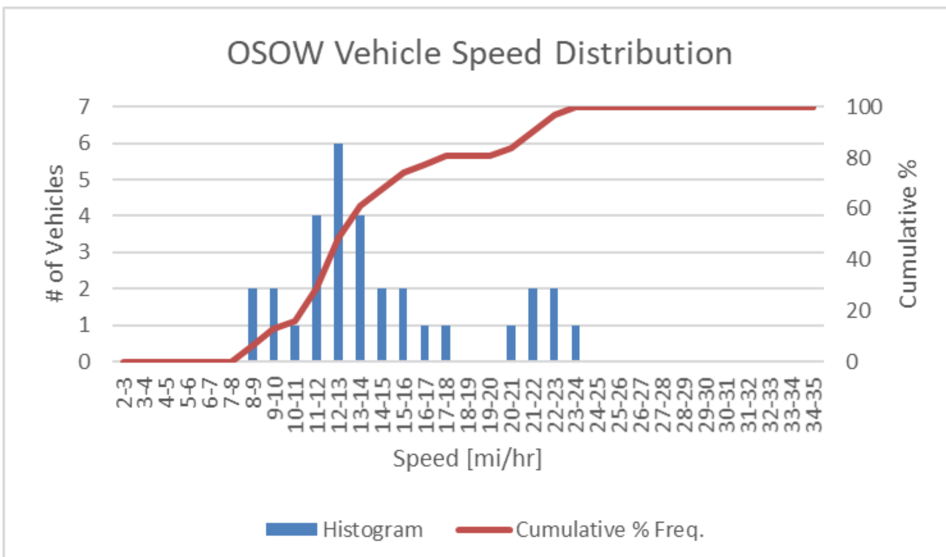



b) Medium Vehicles

**Figure 44. Non-Truck Vehicle Free-Flow Speed Distributions at Fredonia.**




a) Heavy Vehicles




b) OSOW Vehicles

**Figure 45. Truck Free-Flow Speed Distributions at Fredonia.**

These steps for processing the drone dataset to filter out OSOW vehicles and free-flow speed samples provided the necessary data for traffic within the roundabout to input into the simulation model. To produce the final component of the needed data input for simulation, researchers conducted a separate process for developing a free-flow speed data profile for vehicles approaching the roundabout; that process is described in the following section that provides details on activities related to the microsimulation analysis.

## MICROSIMULATION ANALYSIS

As discussed previously, the traditional data collection method did not yield sufficient data for modeling the Katy, Texas, roundabout, while the drone data collection provided extensive data outputs that were sufficient for modeling roundabouts in Kansas. Because the roundabout in Lyndon had a very low OSOW vehicle demand, researchers selected the Fredonia site for the simulation modeling and evaluation.

### Development of Models

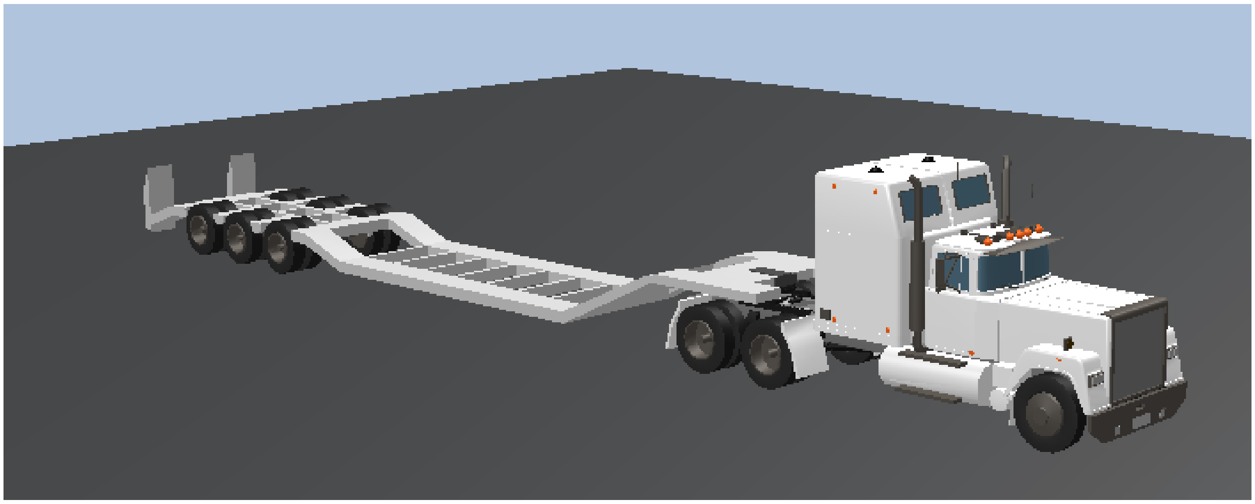
Researchers used the PTV VISSIM software package to develop the simulation models. Factors considered in the simulation evaluation included the size of the roundabout, traffic demand, truck percentage, and OSOW percentage to identify changes in roundabout performance under varying conditions. The research team also included a two-way stop-controlled (TWSC) intersection configuration as an alternative to compare the roundabout with a traditional unsignalized intersection operation that would commonly be found at similar locations.

#### *Modeling the Base Condition*

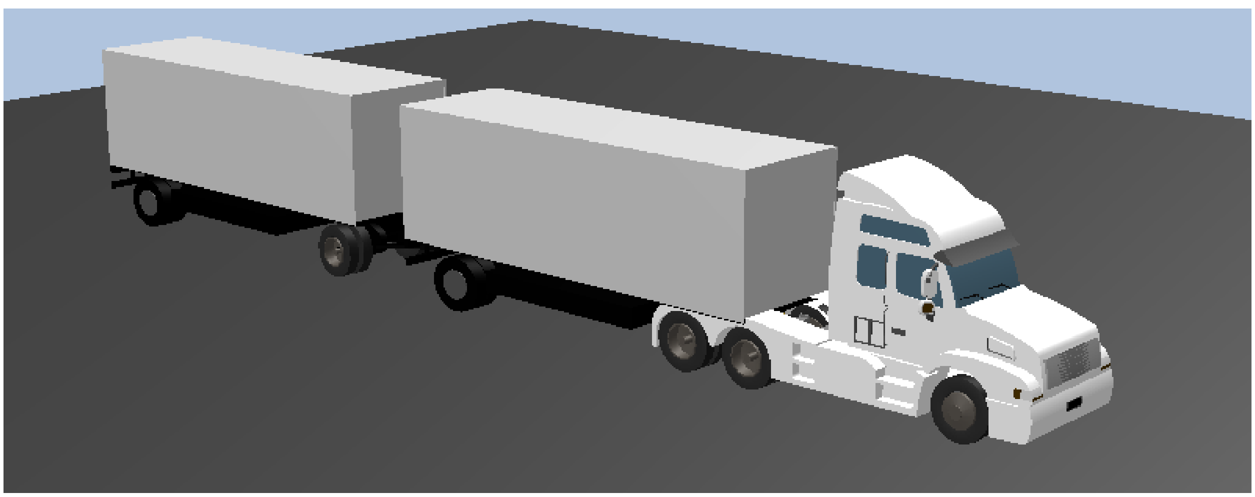
The research team used the drone data collected at the roundabout in Fredonia, Kansas, to model the base condition for the simulation. The drone template image was imported into VISSIM as a background image to aid in matching the different gate zones in the drone data analysis tool to the respective location in the VISSIM networks. The drone data provided the basis for weekday traffic demand (i.e., average daily traffic of approximately 5,000 vpd) and vehicle turning movement counts for different types of vehicles: passenger cars (combination of cars and medium vehicles), heavy trucks, and OSOW trucks (10 percent truck percentage). The drone data was also utilized for calibration of the yield behaviors, spot speeds, and travel times for different type of vehicles. The yielding behavior was modeled using the Priority Rules function in VISSIM which allows different yield behaviors for different vehicle types by using different minimum acceptable temporal and spatial gap parameters. Based on the Gap data from the drone dataset, the research team adjusted the yield behavior parameters so that passenger cars waiting at a yield line accept smaller gaps than heavy trucks before merging into the circulating flow and OSOW vehicles wait for larger gaps than heavy trucks. Two speed profiles were used for each of the four vehicle types: one for the upstream roadway approaching to the roundabout and the other for circulating inside the roundabout. The speed distributions identified from the drone data shown in Figure 44 and Figure 45 were used for the desired circulating speeds.

While the drone was positioned to include at least 100 ft of each leg of the two roundabouts, that distance was not sufficient to provide reliable upstream approach speeds for each approaching vehicle. Speed data were available for many vehicles, but because the approach gate was on the edge of the viewable area, those speed readings were not always generated or did not provide a high level of confidence. Because the drone data did not include the necessary set of approach speeds, researchers used speed profile data from a separate project, RTI Project 0-6997 (*110*), where the speeds were collected on rural Texas highways in several locations. In that project, speed profiles of passenger cars and heavy vehicles were generated using speed data collected on several rural highways in Texas, one of which, US-183, is also a rural two-way two-lane highway with similar characteristics as the approaching highways at the Kansas sites in this project but with a posted speed limit of 75 mph. Because the posted speed limits upstream of the Kansas roundabout approaches were 65 mph, the research team used a speed profile for the simulation model that has the same shape as the speed profile for US-183 but shifted 10 mph lower. Therefore, passenger cars and heavy vehicles approaching and departing the roundabout were assigned the desired speed profiles 10 mph slower than the original 75 mph speed profile. The OSOW vehicles were similarly assigned a speed profile with desired speeds 5 mph slower than the other heavy vehicles generated in the network.

This research project has a key interest in truck behavior at roundabouts and stop-controlled intersections. Therefore, the research team took special care to represent truck acceleration, dimensions, and turning radii when developing the simulation models. The truck acceleration was adjusted from the VISSIM default truck accelerations to match the acceleration from a stop behavior described in the study by Yang et al. (*111*), where they determined truck acceleration for different sizes of trucks from a stop at a ramp meter. The trucks in this VISSIM model followed the acceleration behavior described as Medium Trucks in the Yang study, and the OSOW vehicles followed the acceleration behavior of Heavy Trucks; each of these acceleration behaviors are less aggressive than the default acceleration of trucks in VISSIM. Non-OSOW trucks in this VISSIM model corresponded to dimensions of WB-40 and WB-50 trucks with lengths of 46 and 61 feet, respectively. OSOW trucks in this simulation were represented by a WB-65 truck and a WB-67D truck with two trailers, producing total lengths of 74 feet and 81 feet, respectively. Figure 46 provides 3D images of the OSOW trucks used in simulation.



(a) WB-65



(b) WB-67D with Two Trailers

**Figure 46. 3D Models of OSOW Truck Configurations.**

Through an iterative trial-and-error process of adjusting parameters under the Priority Rule for the yielding behavior of all types of vehicles on individual approaches, the researchers calibrated the base model and verified the calibration with travel times through the roundabout. The calibration results for passenger cars and trucks are shown in Table 16; all of the simulated travel times are within 6.7 sec of the travel times measured from the field using the drone, and most passenger vehicle times are within 0.5 sec.

**Table 16. Average Travel Time Calibration Results.**

| **Passenger Cars** | **WB LT** | **WB RT** | **NB LT** | **EB LT** | **EB TH** | **SB LT** |
|---|---|---|---|---|---|---|
| Field Measurement | 21.1 | 9.7 | 26 | 20.9 | 14.6 | 25.6 |
| Simulation Result | 25.0 | 9.4 | 26.1 | 21.4 | 14.7 | 25.3 |
| Difference | 3.9 | −0.3 | 0.1 | 0.5 | 0.1 | −0.3 |
| **Heavy Trucks** | **WB LT** | **WB RT** | **NB LT** | **EB LT** | **EB TH** | **SB LT** |
| Field Measurement | 28.7 | 12.4 | 23.8 | N/A | 16.4 | 33.3 |
| Simulation Result | 28.5 | 14.4 | 30.5 | 29.5 | 21.1 | 29.0 |
| Difference | −0.2 | 2.0 | 6.7 | N/A | 4.7 | −4.3 |

*Note: N/A = not applicable.*

### *Modeling of the Alternative Scenarios*

Evaluation of alternative scenarios in this project considered the following sets of parameters:

- Intersection configuration and control: roundabout (base condition) and TWSC.
- Roundabout ICD: 180 ft (base condition), 150 ft, and 120 ft.
- ADT: 5,000 vpd (base condition), 10,000 vpd, and 15,000 vpd.
- Truck percentage: 10 (base condition), 20, and 30 percent.
- OSOW percentage: 0 (base condition), 5, and 10 percent.

These parameters were chosen to include a wide variety of conditions that might exist at a rural intersection. The traffic volumes represent those typically seen on rural highways, with the higher volumes representing the potential for future growth in traffic. The base conditions for truck percentage and OSOW percentage likewise represent traffic conditions commonly found on the state highway system; higher percentages were chosen as alternatives to investigate the resiliency of the roundabout at those higher volumes, which would be greater than those seen in most locations but would provide an indication of the capability of roundabouts as an alternative to TWSC intersections. The largest ICD value was chosen as the base condition to be consistent with existing guidance for roundabouts at intersections with high-speed approaches and heavy vehicle volumes, but the smaller diameters were included to provide insight on the sensitivity of the operational performance to that dimension.

Combining the aforementioned parameters results in a set of 96 scenarios for potential modeling by the research team, though not all combinations of parameters were modeled. For example, the scenarios with higher volumes and/or higher truck percentages were associated with high levels of delay for the TWSC configuration as it reached or exceeded its capacity, so lower volumes were simulated first for the TWSC, and as capacity was reached or exceeded, subsequent scenarios with higher volumes were not simulated. Similarly, the OSOW value of 10 percent was not simulated in the scenarios with 10 percent heavy vehicles (which would have implied that all heavy vehicles were OSOW vehicles).

For roundabout scenarios with a smaller ICD, the base condition model was modified with a smaller radius and adjusted to have different circulating speed profiles for different types of vehicles. The FHWA *Roundabouts: An Informational Guide* (*1*) provides the following equation for estimating circulating speeds at roundabouts with different radii:

$$V = \begin{cases} 3.4415R^{0.3861}, & superelevation\ =\ +0.02 \\ 3.4614R^{0.3673}, & superelevation\ =\ -0.02 \end{cases}$$

Where R is measured from the center of the roundabout to the middle of the driving lane.

Using the equation, circulating speeds of the 150-ft and 120-ft ICD scenarios were estimated to be about 1.5 mph and 2.5 mph lower than that of the 180-ft ICD base condition. Therefore, researchers used a circulating speed profile for the two smaller roundabout simulations similar to that of the base condition but with all the desired speeds shifted by 1.5 mph and 2.5 mph lower than the original profile, respectively. The priority rules of the smaller roundabouts kept the same minimum acceptable temporal gaps as the base condition but reduced the minimum acceptable spatial gaps to account for a smaller radius. The research team made extensive efforts to adjust these various parameters to properly model the roundabout scenarios to eliminate crashes caused by aggressive yield behavior and excessively long queues caused by too conservative yield behavior. These adjustments were meticulously applied and involved a detailed iterative process that sought to find the appropriate balance between mitigating irrationally aggressive yielding behavior and unreasonably cautious yielding behavior.

When modeling the TWSC scenarios, the research team assumed a uniform shoulder width of 10 ft on the intersecting roadways, consistent with several TWSC locations near the field data collection sites and other two-lane rural highways. However, early simulation tests revealed a problem with heavy vehicles, particularly OSOW vehicles, being able to complete turning maneuvers within the space available. Therefore, the research team adjusted features at the intersection to accommodate the larger vehicles. In particular, researchers increased the available paved shoulder at the intersection, providing larger turning radii to account for the larger swept path of turning heavy vehicles. The research team assumed that the TWSC intersection would not include any turn lane accommodations (i.e., left-turn lanes or right-turn lanes), and the stop signs that would normally be placed at the intersection were offset about 15 ft upstream to provide additional space for large vehicles to turn even when stopped vehicles were waiting on the intersecting approach. Figure 47 illustrates the settings in the VISSIM model network for these adjustments.

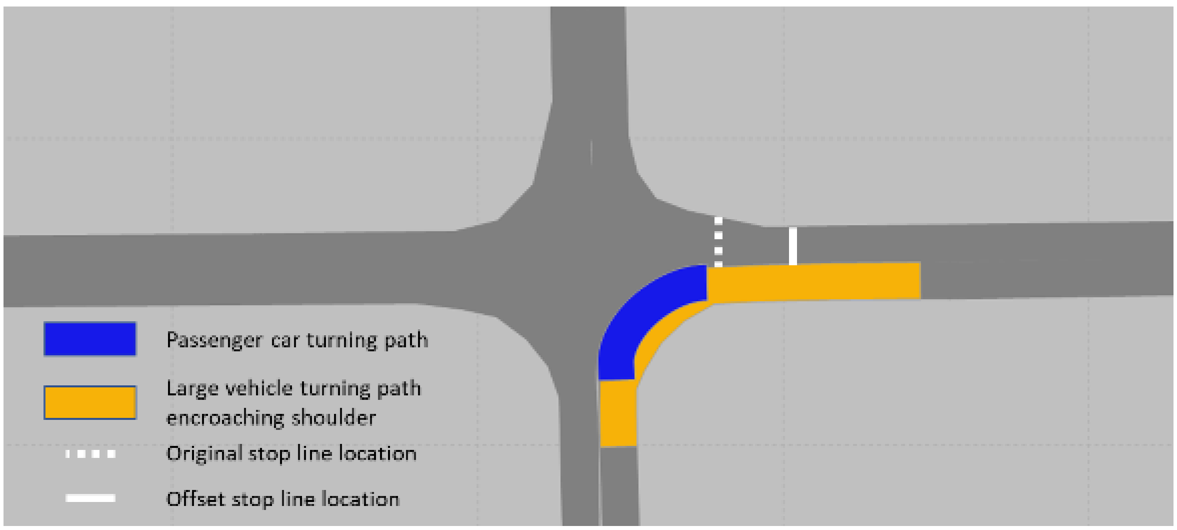
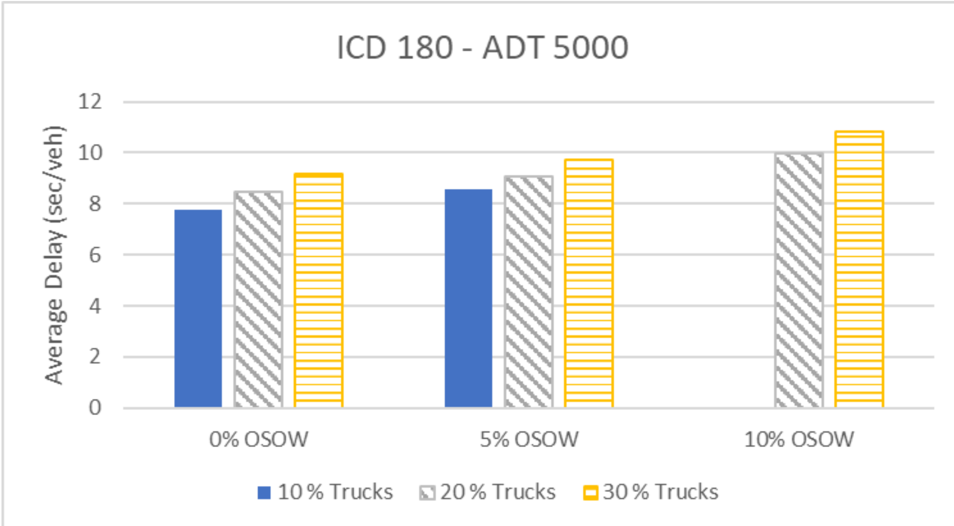



**Figure 47. Right-Turn Paths on NB Approach and Offset Stop Line on WB Approach in Simulation.**

### Results from Analysis

After calibrating the base model and adjusting the parameters of all the scenarios, the research team set the models to have seven simulation runs with different random seeds for each scenario. Each simulation run consisted of a 15-minute warm-up period and a 60-minute simulation duration. The Vehicle Network Performance result data and Node result data were collected from VISSIM for analyzing the effects of different factors on intersection operations.

Figure 48 shows the network average delay of the base geometry and traffic demand condition (ICD of 180 ft and ADT of 5,000 vpd) with a varying truck composition. Under the same traffic demand level, the average delay at the roundabout increased as the truck percentage increased. Given the same truck demand, the increase in OSOW vehicles caused higher traffic delay. The same trend was observed under other scenarios with a different roundabout diameter and overall demand level.




Note: 10 percent OSOW was not considered for 10 percent Truck scenario.

**Figure 48. Simulation Results of Average Delay of ICD 180—ADT 5,000 Scenarios.**

Figure 49 shows the average delay of the roundabout with a 180-ft ICD, varying total traffic and truck demand when the OSOW percentage is fixed at 5 percent. The results indicate that the increase in total traffic demand and truck demand both caused an increase in the average delay. The delay increase became larger as the overall demand increased. The same trend was observed under other scenarios with a different roundabout diameter and OSOW demand level.

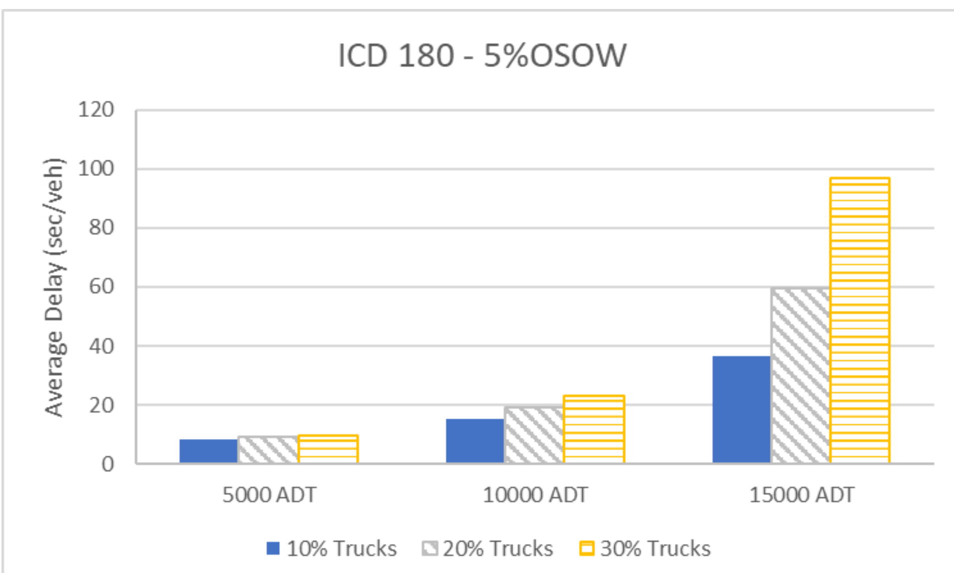



**Figure 49. Simulation Results of Average Delay of ICD 180—5 Percent OSOW Scenarios.**

Figure 50 shows the capability of roundabouts of different diameters in accommodating different levels of truck demand under the same overall traffic demand (10,000 vpd ADT) and

OSOW demand (5 percent). As expected, the larger roundabout produced lower delay than the smaller roundabouts across all levels of truck demand. The same trend was observed under other scenarios with a different overall demand and OSOW demand level.

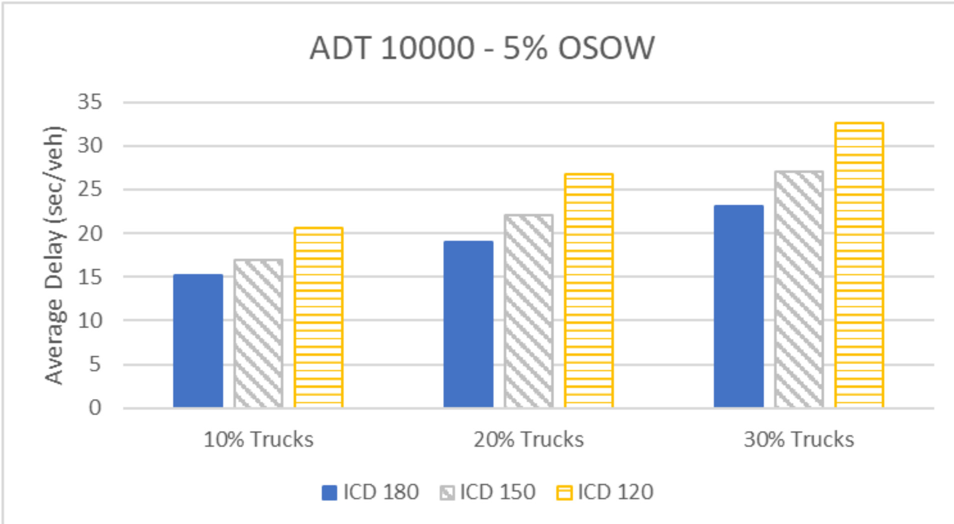



**Figure 50. Simulated Average Delay of ADT 10,000—5 Percent OSOW Scenarios.**

Figure 51 shows the average delay under different operation methods when the overall traffic demand and OSOW demand remained the base condition but with a varying truck percentage. The results clearly showed that the TWSC scenarios yielded a much higher delay than the roundabout scenarios. The same trend was observed under other scenarios across different overall demand and OSOW demand levels.

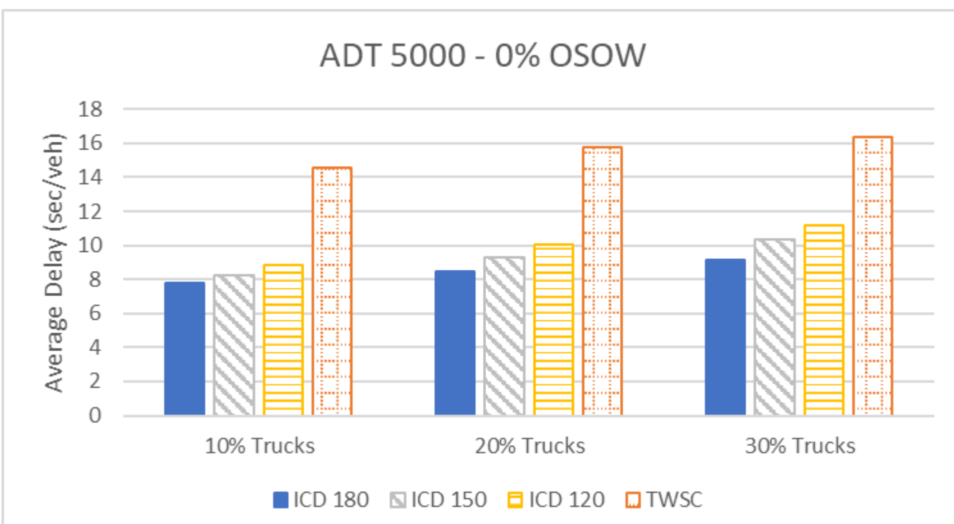
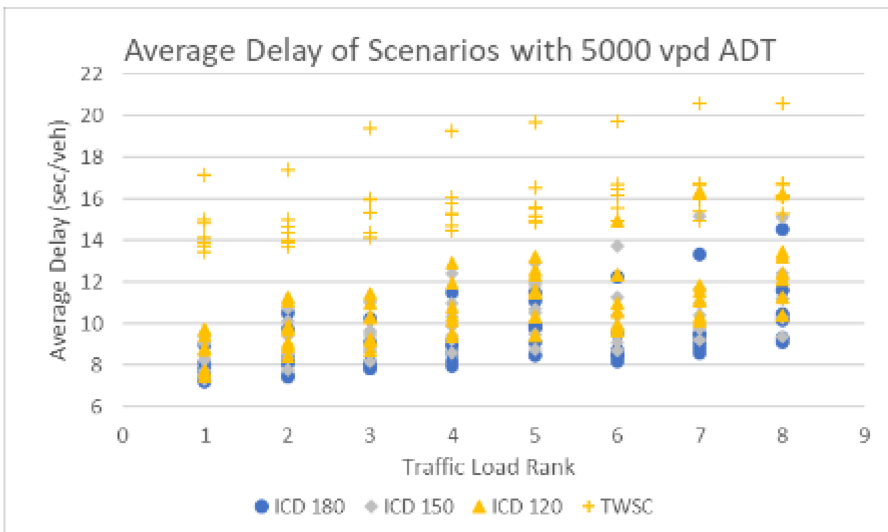
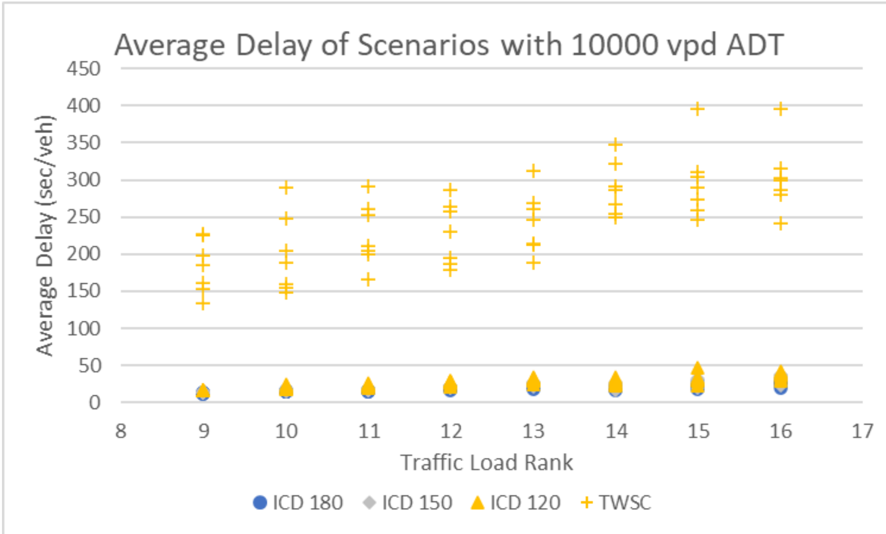



**Figure 51. Simulated Average Delay of ADT 5,000—0 Percent OSOW Scenarios.**

Considering the levels of overall traffic demand and normal truck or OSOW vehicle demand as a traffic load at an intersection, traffic loads simulated in this research can be ranked from the lightest load (5,000 vpd ADT, 10 percent truck, and 0 percent OSOW) to the heaviest load (15,000 vpd ADT, 30 percent trucks, and 10 percent OSOW vehicles) with other combinations of overall demand and normal truck or OSOW demand in between (a total of 24 combinations). The simulated average delay can be plotted against the traffic load applied at the intersection. Figure 52 shows such plots for scenarios with 5,000 vpd ADT and 10,000 vpd ADT. The results indicate that both roundabout and TWSC intersections operated well under a low traffic demand condition (5,000 vpd ADT) with delays generally less than 20 seconds per vehicle. The roundabout operation started to outperform the TWSC operation when the traffic demand increased (10,000 vpd ADT); roundabout delays were less than 50 seconds per vehicle and TWSC delays generally exceeded 150 seconds per vehicle. The plot for the 15,000 ADT scenario was not developed for TWSC because that volume exceeded the intersection's capacity.




**(a) 5,000 ADT**




**(b) 10,000 ADT**

(Note: Lowest ADT and Truck or OSOW percent indicates lowest traffic load rank).

**Figure 52. Average Delay of Low- and Medium-Demand Scenarios by Traffic Load Rank.**

Roundabout scenarios with a 180-ft or 150-ft ICD were able to accommodate all traffic loads without leaving vehicles outside the network when the simulation period ended. The roundabout with a 120-ft ICD had unserved vehicles for scenarios with a traffic load of 15,000 vpd ADT and 30 percent truck traffic. The TWSC operation had unserved vehicles for a traffic load of 10,000 vpd ADT and 30 percent truck traffic, as well as for all scenarios with a traffic load of 15,000 vpd ADT. Figure 53 plots delay versus traffic load for the roundabout scenarios under the high traffic demand level (15,000 vpd ADT). Because this traffic demand level appeared to be much higher than the capacity of the considered TWSC intersection, results of the TWSC operation were excluded from the analysis. As shown in Figure 53, roundabouts with larger ICDs (180 ft or 150 ft) performed better than those with smaller ICDs, and the difference became more apparent as the traffic load level increased.

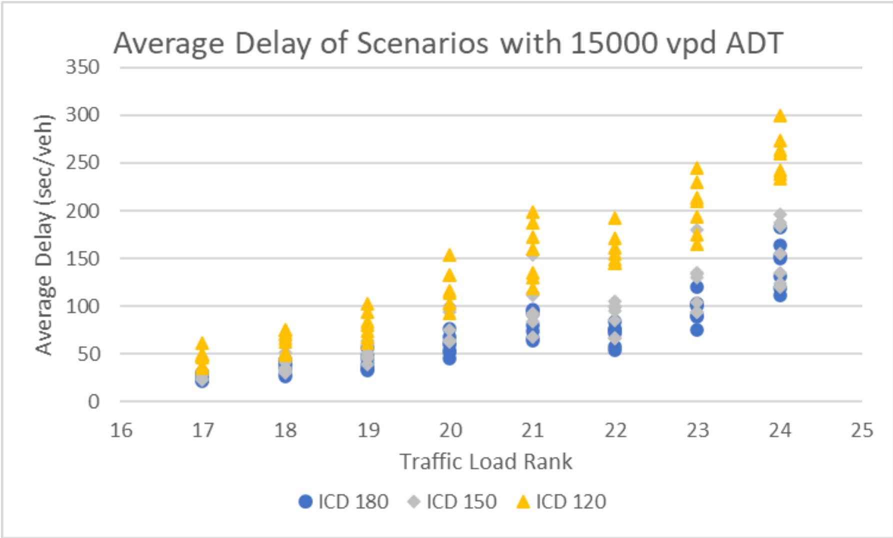



**Figure 53. Average Delay of High-Demand Roundabout Scenarios by Traffic Load Rank.**

The Node results from VISSIM containing the level of service (LOS) information of individual scenarios provided further evidence for evaluation of the suitability of intersection alternatives under different traffic load levels. Table 17 shows the LOS by vehicle type for the individual scenarios.

## Table 17. Level of Service by Vehicle Type under Different Traffic Load Levels.

| Traffic Load | ICD 180 ft | | | | ICD 150 ft | | | | ICD 120 ft | | | | TWSC | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | All | Car | Truck | OSOW | All | Car | Truck | OSOW | All | Car | Truck | OSOW | All | Car | Truck | OSOW |
| 5000 ADT_10% Truck_0% OSOW | A | A | A | N/A | A | A | A | N/A | A | A | B | N/A | B | B | B | N/A |
| 5000 ADT_10% Truck_5% OSOW | A | A | A | B | A | A | B | B | A | A | B | B | B | B | A | B |
| 5000 ADT_20% Truck_0% OSOW | A | A | A | N/A | A | A | A | N/A | A | A | B | N/A | B | B | B | N/A |
| 5000 ADT_20% Truck_5% OSOW | A | A | A | B | A | A | B | B | A | A | B | B | B | B | B | B |
| 5000 ADT_20% Truck_10% OSOW | A | A | A | B | A | A | B | B | A | A | B | C | B | B | B | B |
| 5000 ADT_30% Truck_0% OSOW | A | A | A | N/A | A | A | A | N/A | A | A | A | N/A | B | B | B | N/A |
| 5000 ADT_30% Truck_5% OSOW | A | A | A | B | A | A | A | B | A | A | B | C | B | B | B | B |
| 5000 ADT_30% Truck_10% OSOW | A | A | A | B | A | A | B | B | A | A | B | C | B | B | B | B |
| 10000 ADT_10% Truck_0% OSOW | A | A | B | N/A | A | A | C | N/A | B | A | C | N/A | F | F | F | N/A |
| 10000 ADT_10% Truck_5% OSOW | A | A | C | C | B | A | C | D | C | B | D | D | F | F | F | F |
| 10000 ADT_20% Truck_0% OSOW | B | A | C | N/A | B | A | C | N/A | C | C | D | N/A | F | F | F | N/A |
| 10000 ADT_20% Truck_5% OSOW | B | B | C | D | C | B | D | D | C | C | D | E | F | F | F | F |
| 10000 ADT_20% Truck_10% OSOW | C | B | C | D | C | C | D | D | C | C | D | E | F | F | F | F |
| 10000 ADT_30% Truck_0% OSOW | B | B | C | N/A | C | B | D | N/A | C | C | D | N/A | F | F | F | N/A |
| 10000 ADT_30% Truck_5% OSOW | C | B | C | D | C | C | D | D | D | C | E | E | F | F | F | F |
| 10000 ADT_30% Truck_10% OSOW | C | C | D | D | D | C | E | E | D | D | E | E | F | F | F | F |
| 15000 ADT_10% Truck_0% OSOW | C | C | D | N/A | C | C | E | N/A | E | E | F | N/A | F | F | F | N/A |
| 15000 ADT_10% Truck_5% OSOW | D | D | E | E | D | D | E | F | F | E | F | F | F | F | F | F |
| 15000 ADT_20% Truck_0% OSOW | D | D | E | N/A | E | E | F | N/A | F | F | F | N/A | F | F | F | N/A |
| 15000 ADT_20% Truck_5% OSOW | E | E | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| 15000 ADT_20% Truck_10% OSOW | F | F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| 15000 ADT_30% Truck_0% OSOW | F | E | F | N/A | F | F | F | N/A | F | F | F | N/A | F | F | F | N/A |
| 15000 ADT_30% Truck_5% OSOW | F | F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |
| 15000 ADT_30% Truck_10% OSOW | F | F | F | F | F | F | F | F | F | F | F | F | F | F | F | F |

Comparing LOS of different operation methods, the TWSC intersection overall performed the poorest across all demand levels. While performing at a LOS B or better under the 5,000 vpd ADT demand level, TWSC operation yielded a LOS F when the demand was 10,000 vpd or higher for all types of vehicles. The 120-ft ICD roundabout provided a LOS A for passenger cars and a LOS B (or better) for normal trucks under the 5,000 vpd ADT demand level, but it produced a LOS C for OSOW vehicles when the OSOW demand increased. This inferior performance in accommodating increased OSOW demand was not observed for the TSWC operation. This indicates that, while not suitable for a demand level of 10,000 vpd ADT or higher, the TWSC operation might perform better than the small roundabout (120 ft ICD) for accommodating a high OSOW demand when the overall traffic demand is low (5,000 vpd ADT). The roundabout with 120-ft ICD was able to provide an average LOS C for all vehicles under most scenarios of the 10,000 vpd ADT demand level (except those with a truck demand of 30 percent and OSOW of 5 percent or higher), but a LOS D resulted for trucks when the truck demand was 10 percent (with 5 percent OSOW) or higher. This small roundabout would not be expected to perform well under a high traffic demand condition (i.e., 15,000 vpd ADT).

The larger roundabouts (180-ft ICD and 150-ft ICD) yielded a LOS B or better for all types of vehicles under the low demand level (5,000 vpd ADT). The 150-ft ICD roundabout provided a LOS C for trucks beginning at 10,000 vpd ADT while maintaining an overall LOS C or better for a traffic load up to 30 percent trucks and 5 percent OSOW. The 180-ft ICD roundabout provided a LOS C or better for all the scenarios under 10,000 vpd ADT and was able to accommodate normal trucks with a LOS C or better when OSOW demand was not higher than 5 percent. Under the high traffic demand level (15,000 vpd ADT), the two larger roundabouts performed similarly in that only the 10 percent truck scenario had a LOS C for overall traffic, but the 180-ft ICD roundabout accommodated large vehicles (normal trucks and OSOW vehicles) better than the 150-ft ICD when the truck demand was 20 percent or lower and OSOW was 5 percent or lower.

# CHAPTER 5: FIELD STUDY OF INNOVATIVE INTERSECTIONS

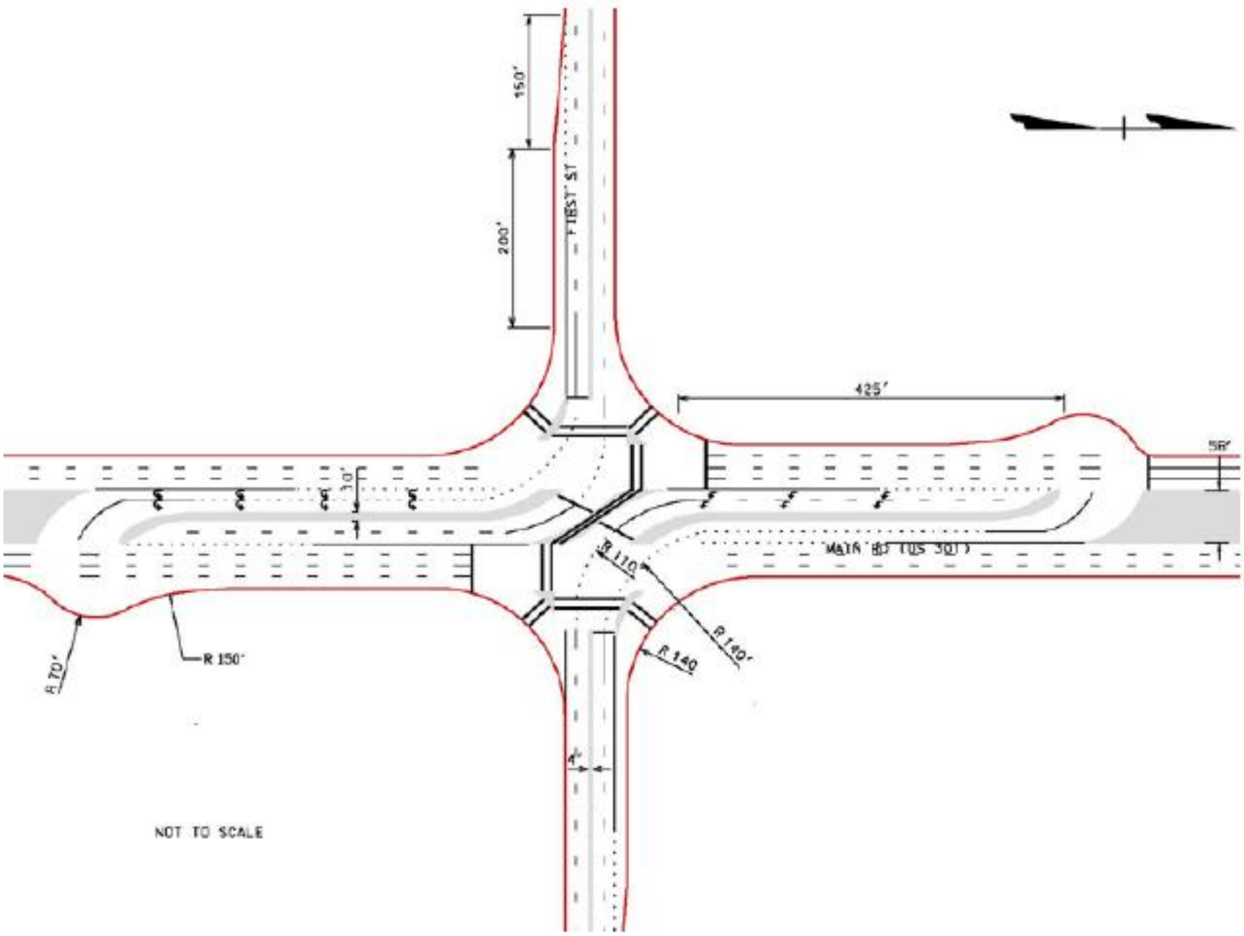
This chapter summarizes the efforts and findings for field studies of two existing RCUT intersections along with a simulation effort to investigate spacing needs between the main intersection and the U-turn lanes. This task included reviewing the literature, selecting the best intersections for the field study, collecting field data, constructing simulation models, and finally evaluating the findings. Efforts to conduct each of the mentioned subtasks are explained in this chapter. An in-depth literature review was conducted earlier in Task 3, and the content of that review is provided in Chapter 3 of this report. Key findings from the literature review used in Task 7 are summarized in this chapter.

## KEY REFERENCE DOCUMENTS

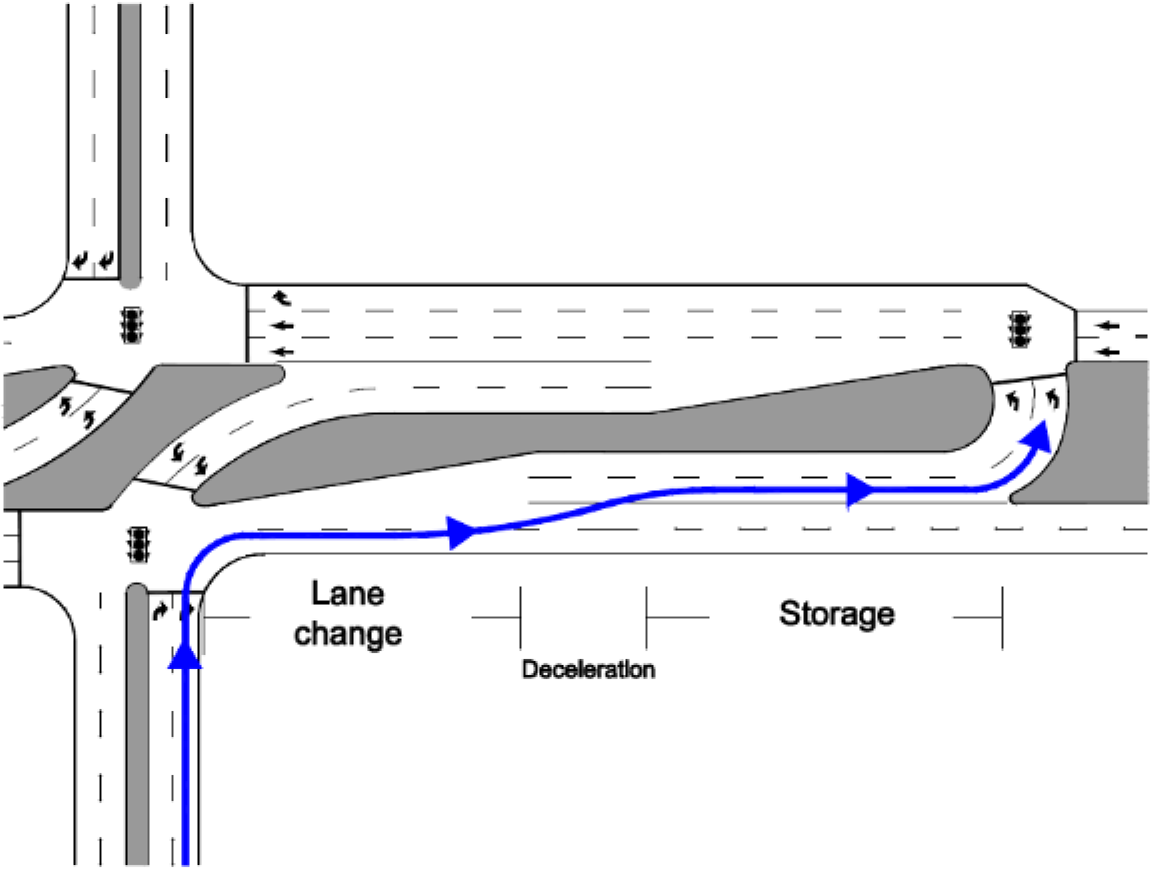
RCUT intersections have unique design principles that are not typically present at a conventional intersection (e.g., a median wide enough to accommodate the U-turn movements, or the provision of bump-outs or loons to facilitate the turning traffic). Several documents provide guidance on the intersection form including:

- The 2010 *Alternative Intersection/Interchanges: Informational Report* (*33*).
- The 2014 *Restricted Crossing U-Turn Intersection: Informational Guide* (*35*).

Another key in RCUT intersection designs is providing the optimum spacing between the main intersection and median U-turn crossovers at the RCUT intersection. Enough spacing is needed to provide a smooth weaving process and perhaps enough length at the U-turn lanes for vehicle storage. Long spacing can increase the travel time and delay for motorist, while short spacing can result in queuing overflowing to nearby intersections. The recommendations for this length vary, with 400- to 600-ft spacing recommended for signalized crossovers in the AASHTO *Green Book* (*27*), 425-ft spacing in the AIIR (*33*), as illustrated in Figure 54, and 660 feet ± 100 feet between the main intersection and the U-turn crossover as reported in Hummer et al. (*35*), who state that the dimension is based in part on the deceleration length required for the major street having a posted speed limit of 45 mph (see example in Figure 55).




Source: Figure 89 in Hughes et al. (33).
**Figure 54. Typical RCUT Plan View with Crossovers on Mainline Approaches.**




Source: Exhibit 7-22 in Hummer et al. (35).
**Figure 55. Spacing Consideration for a Minor Street Through or Left Movement.**

## LITERATURE REVIEW

This literature review summarizes recent research for RCUTs and is organized into two sections: safety evaluations and operational evaluations.

### Safety Evaluations

Safety evaluations of RCUTs started with consideration of the number of conflict points; however, with the greater number of installations, evaluations using crashes have been able to identify statistically significant crash modification factors (CMFs).

The AIIR noted that RCUT intersections are effective in crash reduction (*33*). This conclusion was based on RCUTs and MUTs having a lower number of conflict points compared with conventional intersections (16 for MUTs and 14 for RCUTs compared to 32 for four-leg intersections) and a safety evaluation of three locations.

In 2017 Hummer and Rao (*112*) evaluated safety for 11 RCUT intersections. They recommended a CMF of 0.85 for overall crashes and 0.78 for injury crashes for the conversion of a conventional intersection to an RCUT intersection. In 2013 Inman et al. (*113*) considered several approaches to evaluate the safety benefits of converting conventional intersections into RCUTs along two Maryland highway corridors. They concluded that RCUT intersections have 44 percent fewer crashes compared to conventional intersections and also have an overall reduction in crash severity.

In 2017 Edara et al. (*52*) examined crashes that occurred at 12 existing J-turn sites in Missouri and found the following proportions of five crash types:

- Major road sideswipe = 31.6 percent.
- Major road rear-end = 28.1 percent.
- Minor road rear-end = 15.8 percent.
- Loss of control = 14 percent.
- Merging from U-turn = 10.5 percent.

Edara et al. (*52*) also found that the crash rates for both sideswipe and rear-end crashes decreased with an increase in the spacing from the minor road to the U-turn; J-turns with a spacing of 1,500 ft or greater experienced the lowest crash rates. Based on the crash review and simulation findings (discussed below), the authors recommended that acceleration lanes be used for all J-turn designs, including lower volume sites. They also stated that while space between 1,000 and 2,000 ft was found to be sufficient for low-volume combinations, a spacing of 2,000 ft was recommended for medium- to high-volume conditions.

In 2020 Al-Omari et al. (*114*) reported on a safety study that used data for 12 RCUT signalized intersections. They used three methods to identify crashes: (a) a 250-ft radius circular buffer from the center of the main intersection (same as the traditional approach), (b) a large circular buffer that would cover all intersection-related areas (i.e., the main intersection and both crossovers), and (c) a 250-ft radius circular buffer from the center of the main intersection and a 50-ft radius circular buffer from the center of both crossovers. The third scenario (250-ft main buffer plus two 50-ft median U-turn crossover buffers) was considered the most reasonable because it covered all the intersection-related areas without including crashes not relevant to the intersection; the third scenario was used in their study.

The following CMFs were identified for RCUTs using a before–after with comparison group methodology and significant at 95 percent confidence level:

- Total crashes CMF = 0.7632.
- Fatal-and-injury crashes CMF = 0.5669.
- Injury crashes CMF = 0.5726.
- Property damage only (PDO) crashes CMF = 0.8414.
- Angle crashes CMF = 0.5854.
- Head-on crashes CMF = 0.0667.
- Rear-end crashes CMF = 0.7511.
- Opposite direction sideswipe crashes CMF = 0.3299.

No significant changes were found for single-vehicle and same-direction sideswipe crashes at RCUT intersections.

**Operational Evaluations**

Hughes et al. (*33*) reported in 2010 that the optimum operational performance of the RCUT intersection is subject to the ratio between the minor road and the intersection volumes. They found that the RCUT intersection experienced a higher throughput and less travel time than the conventional intersection only at ratios of less than 0.2 and 0.15, respectively. Bared (*115*) found in 2009 that the RCUT intersection with a low minor road traffic volume level (i.e., less than 20 percent of the total number of vehicles entering the intersection) has a 30 percent higher capacity and 40 percent lower network travel time than the signalized conventional intersection. These advantages were also reported by Doctor (*116*) in 2013 using case study findings for RCUTs in Michigan:

- Throughput (i.e., the number of vehicles exiting the intersection) increased up to 30 percent.
- Network intersection travel time decreased up to 40 percent.

Edara et al. (*52*, *117*) reported on a microsimulation effort to investigate the presence or absence of acceleration lanes and the distance between the minor road and the U-turn (1,000 ft, 2,000 ft, and 3,000 ft). They assumed the 85th percentile speeds of 75 mph for passenger cars, 70 mph for trucks, and 64 mph for merging vehicles from the minor road. The 12 volume scenarios considered are provided in Table 18. The 12 volume scenarios, three U-turn distances (1,000, 2,000, and 3,000 ft), and two acceleration lane conditions (present or absent) resulted in a total of 72 combinations. The SSAM package within VISSIM was used to identify the number of conflicts for the combinations. The results were consistent for all volume scenarios. The number of conflicts decreased with an increase in the spacing between the minor road and the U-turn; however, not in a lineal manner. The authors concluded that a spacing of 2,000 ft would be sufficient to provide a good trade-off between safety and a cost-effective J-turn design.

In general, the lack of an acceleration lane increased the queuing on the minor road for vehicles waiting for a gap to merge onto the major road. The presence of acceleration lanes resulted in better safety for all spacing and volume combinations. The resulting minimum spacing for each volume scenario is provided in Table 19 (*118*).

**Table 18. Volume Scenarios Used by Edara et al. (*52*).**

| No. | Major Road Total (vph) | Minor Road Crossing[1] (vph) | Minor Road Right Turn (vph) | Total Minor/ Major Ratio |
|---|---|---|---|---|
| 1 | 1,000 | 150 | 150 | 30% |
| 2 | 1,000 | 250 | 250 | 50% |
| 3 | 1,000 | 350 | 350 | 70% |
| 4 | 1,300 | 195 | 195 | 30% |
| 5 | 1,300 | 325 | 325 | 50% |
| 6 | 1,300 | 455 | 455 | 70% |
| 7 | 1,504 | 226 | 226 | 30% |
| 8 | 1,504 | 376 | 376 | 50% |
| 9 | 1,504 | 526 | 526 | 70% |
| 10 | 1,800 | 270 | 270 | 30% |
| 11 | 1,800 | 450 | 450 | 50% |
| 12 | 1,800 | 630 | 630 | 70% |

*Note: [1] Includes both minor road left turns and minor road through movements.*

**Table 19. Sun and Edara (*118*) Recommended Minimum Spacing for Each Scenario.**

| Major Road Total (vph) | Minor Road Crossing (left and through) (vph) | Minor Crossing (right) (vph) | Total Minor/Major | With Acceleration Lane (ft) | No Acceleration Lane (ft) |
|---|---|---|---|---|---|
| 1,000 | 150 | 150 | 30% | 1,000–2,000 | 1,000 |
| | 250 | 250 | 50% | 1,000–2,000 | 1,000 |
| | 350 | 350 | 70% | 2,000 | 1,000 |
| 1,300 | 195 | 195 | 30% | 1,000–2,000 | Not preferred |
| | 325 | 325 | 50% | 2,000 | Not preferred |
| | 455 | 455 | 70% | 2,000–3,000 | Not preferred |
| 1,500 | 226 | 226 | 30% | 2,000 | Not preferred |
| | 376 | 376 | 50% | > 2,000 | Not preferred |
| | 526 | 526 | 70% | > 2,000 | Not preferred |
| 1,800 | 270 | 270 | 30% | 2,000 | Not preferred |
| | 450 | 450 | 50% | 2,000 | Not preferred |
| | 630 | 630 | 70% | 3,000 | Not preferred |

In 2021 Al-Omari and Abdel-Aty (*119*) compared a new intersection design they termed "Shifting Movements" to conventional and RCUT intersection forms using simulation. Average control delay and throughput were the measures used to compare the intersection forms at three levels (intersection, road, and movement). When comparing the conventional intersection to the RCUT using average intersection delay, the RCUT was preferred when total entering vehicles (TEV) was 6,625 vph and 20 percent left turns. Conventional intersections performed better at low total entering volumes and left-turn proportions. Their results also illustrated that the RCUT intersection design has poor operational performance at moderate to heavy minor road traffic (more than 20 percent of TEV). The reason is the high travel time of the minor through and left-turn traffic at the RCUT intersection, which could stop three potential times since it must pass through the median U-turn crossovers.

## FIELD STUDIES

### Potential Locations

For the field studies, the research team was interested in study sites that could represent a typical RCUT intersection and could be the base for simulation that would test several different scenarios. In total 52 RCUT intersections were identified and reviewed further. After comparing selected locations and evaluating availability of extra information such as signal timing plans, building timelines, and geometric site specifications, two RCUT sites were selected. Table 20 lists the candidates along with their geographical location.

**Table 20. Selected RCUT Intersections.**

| Site Name | City, State | Main Road | Cross Road | Latitude | Longitude |
|---|---|---|---|---|---|
| NC-IT: US-74 and Sardis Church Road | Indian Trails, NC | US-74 | Sardis Church Road | 35°05'01.8"N | 80°39'38.2"W |
| NC-MO: US-74 and Faith Church Road | Monroe, NC | US-74 | Faith Church Road | 35°05'01.8"N | 80°39'38.2"W |

## Study Site Characteristics

The selected sites were located along US Highway 74, east of Charlotte, NC. US-74 is 515 miles in its entire length, from Chattanooga, TN, to Wrightsville Beach, NC. In North Carolina, US-74 connects three major cities (Asheville, Charlotte, and Wilmington) and runs through a variety of urban and rural locations. The two study sites are located near each other, and US-74 has two main lanes per direction in their vicinity in addition to exclusive right-turn and left-turn lanes.

The study site in Indian Trails is located at the intersection of US-74 (known locally as Independence Expressway or Andrew Jackson Hwy) and Sardis Church Road, which is also called Wesley Chapel Stouts Rd. US-74 has two through lanes near the intersection along with exclusive left-turn and right-turn lanes. The U-turn lanes are located about 1,000 ft on either side of the main intersection. Figure 56 provides an overview of the corridor. Note that the U-turn intersection east of the main intersection has two lanes, while the U-turn intersection on the west side has one lane.


Source: Base image from Google Earth.

**Figure 56. NC-IT: US-74 and Sardis Church Road Corridor.**

The Monroe study site is located at the intersection of the US-74 and Faith Church Road. A large distribution center for a grocery store chain is located at the south side of the intersection and feeds directly into the intersection. Similar to the Sardis Church Road study site, US-74 at Faith Church Road has two through lanes along with exclusive left-turn and right-turn lanes at the main intersection. Figure 57 provides an overview of the corridor.


Source: Base image from Google Earth.

**Figure 57. NC-IT: US-74 and Faith Church Road Corridor.**

**Data Collection**

*NC-IT: US-74 and Sardis Church Road*

Data collection for the US-74 and Sardis Church Road study site was completed using drone-mounted cameras. To cover the roughly 2,000-ft highway segment, a set of five drones were used. Figure 58 shows the entire study segment with five rectangular frames representing areas that each of the cameras covered. Each rectangle is drawn with a different line type and color to match the border styles used in Figure 59 to Figure 63, which show a closeup of the roadway layout for each camera view.


Source: Base image from Google Earth.
**Figure 58. Sardis Church Lane Study Site Map View and Camera Coverage.**

**Figure 59. West U-Turn Intersection Camera View at Sardis Church Road Site.**

**Figure 60. West Middle Segment Camera View at Sardis Church Road Site.**

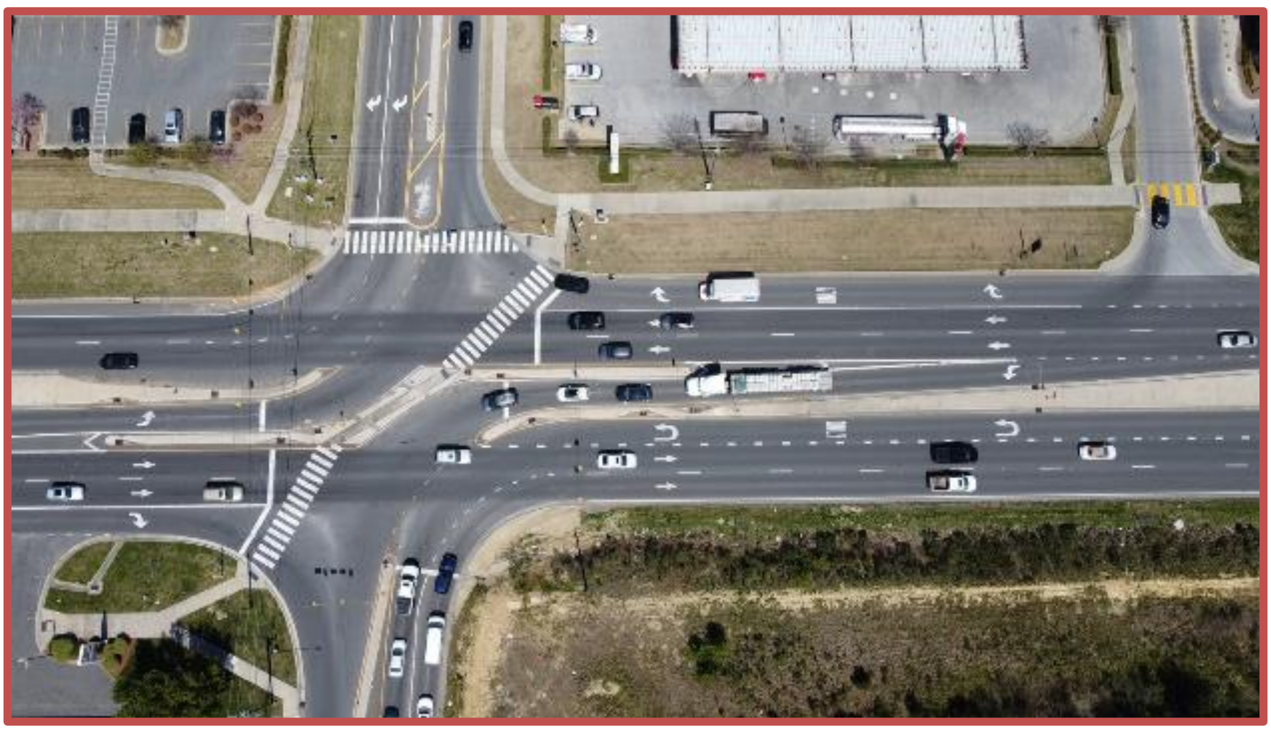


**Figure 61. Main Intersection Camera View at Sardis Church Road Site.**

**Figure 62. East Middle Segment Camera View at Sardis Church Road Site.**

**Figure 63. East U-Turn Intersection Camera View at Sardis Church Road Site.**

One of the limitations of drone data collection is their short battery life compared to regular data collection. Drones used for video data collection were usually capable of recording around 15 minutes of data before replacement of the battery is needed. This period could be shorter if the drone unit encountered wind or higher temperatures. For the Sardis Church Road site, several attempts were made to collect the data; however, rain and fog delayed two initial attempts. On April 13, 2021, video data were collected at all five segments. Attempts were made to combine all five videos into one view so that post-processing of the video could collect data on travel times throughout the corridor. Several challenges were encountered with this approach including coordination between drone operators in having the drone in the air and collecting video data at the same time. Video image processing was used on approximately 13 minutes of video data available for all five views. The reduced data was used to calibrate and validate the simulation models. The processed information included vehicle counts, vehicle classification, and travel time.

Researchers manually reduced the data from all video files that recorded U-turning vehicles; a summary of that dataset is provided in a following section of this chapter.

*NC-IT: US-74 and Faith Church Road*

Data collection for the US-74 and Faith Church Road site was conducted on June 30, 2021, using two drone-mounted cameras that were positioned such that each could cover half of the study segment. Similar to the Sardis Church Road study site, the Faith Church study segment was around 2,000 feet long and required multiple cameras to cover the entire segment.

Figure 64 shows the entire segment with two rectangles showing the areas covered with each of the cameras. In contrast to the Sardis Church site, the cameras at the Faith Church site were not positioned directly over the data collection area. Rather, the viewing angle looking at the corridor from either end was able to cover nearly 1,000 feet each.


Source: Base image from Google Earth.

**Figure 64. Faith Church Road Study Site Map View and Camera Coverage.**

**Figure 65. East Segment Camera View at Faith Church Road Site.**

**Figure 66. West Segment Camera View at Faith Church Road Site.**

**Findings and Results**

*NC-IT: US-74 and Sardis Church Road*

For the Sardis Church site, one set of the video files were reduced with video image processing and the data were used to calibrate the simulation models (see following section). The software used to post-process the video used a set of entry and exit gates, and each vehicle's entry and exit were logged when it passed through these gates.

Figure 67 shows the entry (green) and exit (red) gates for the Sardis Church Road study site. After the entries and exits were logged, researchers generated an origin-destination (O-D) matrix that shows the number of vehicles entering from an entry gate and exiting through an exit gate. Table 21 shows the descriptions for each gate, and Table 22 shows the volume O-D matrix for all vehicles.


Source: Base image from Google Earth.

**Figure 67. Entry (Green) and Exit (Red) Gates Used for Data Reduction at Sardis Church Road Site.**

**Table 21. Gate Number Descriptions for Sardis Church Road Site.**

| Gate Name | Description | Gate Name | Description |
|---|---|---|---|
| Entry Gate 24 | Sardis North to US-74 West | Exit Gate 23 | US-74 West RCUT Exit |
| Entry Gate 26 | US-74 Westbound | Exit Gate 25 | US-74 Westbound Exit |
| Entry Gate 27 | Lowes Pk Lot to US-74 East | Exit Gate 28 | US-74 East to Lowes Pk Lot |
| Entry Gate 30 | Sardis South to US-74 East | Exit Gate 29 | US-74 Westbound to Sardis South |
| Entry Gate 33 | US-74 Westbound Before RCUT | Exit Gate 32 | US-74 East RCUT Exit |
| Entry Gate 35 | Car Wash to US-74 4 West | Exit Gate 34 | US-74 West to Carwash |
| Entry Gate 37 | QuikTrip to US-74 West | Exit Gate 36 | US-74 West to QuikTrip |
| Entry Gate 39 | US-74 Eastbound Before RCUT | Exit Gate 38 | US-74 Westbound Exit |
| Entry Gate 40 | US-74 East RCUT Entry | Exit Gate 42 | US-74 Eastbound to Sardis North |
| Entry Gate 41 | US-74 West RCUT Entry | Exit Gate 44 | Sardis North Exit |
| Entry Gate 43 | US-74 Eastbound to Sardis North | Exit Gate 45 | Sardis South Exit |

**Table 22. All Vehicles Origin-Destination Matrix for Sardis Church Road Site.**

| **Gates** | **Ent 23** | **Ent 25** | **Ent 28** | **Ent 29** | **Ent 32** | **Ent 34** | **Ent 36** | **Ent 38** | **Ent 42** | **Ent 44** | **Ent 45** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Exit 24** | 5 | 27 | 4 | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 22 |
| **Exit 26** | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Exit 27** | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 16 | 0 | 14 | 1 |
| **Exit 30** | 0 | 43 | 0 | 0 | 10 | 0 | 10 | 35 | 0 | 23 | 0 |
| **Exit 33** | 0 | 261 | 1 | 0 | 0 | 3 | 17 | 2 | 0 | 18 | 29 |
| **Exit 35** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Exit 37** | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 3 |
| **Exit 39** | 0 | 0 | 15 | 0 | 2 | 0 | 1 | 185 | 0 | 24 | 85 |
| **Exit 40** | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Exit 41** | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 |
| **Exit 43** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 |

The interface has the ability to classify the objects in the video. The following classes were used in this study: undefined, car, medium vehicle, heavy vehicle, bus, motorcycle, and bicycle. While Table 22 shows volume data for all of the vehicle classes, the majority of the vehicles were cars. Table 23 shows the volume O-D matrix for cars only.

**Table 23. Passenger Cars Origin-Destination Matrix for Sardis Church Road Site.**

| Gates | Ent 23 | Ent 25 | Ent 28 | Ent 29 | Ent 32 | Ent 34 | Ent 36 | Ent 38 | Ent 42 | Ent 44 | Ent 45 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Exit 24** | 5 | 26 | 4 | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 22 |
| **Exit 26** | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Exit 27** | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 16 | 0 | 14 | 1 |
| **Exit 30** | 0 | 41 | 0 | 0 | 8 | 0 | 7 | 32 | 0 | 22 | 0 |
| **Exit 33** | 0 | 234 | 1 | 0 | 0 | 2 | 15 | 2 | 0 | 14 | 27 |
| **Exit 35** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| **Exit 37** | 0 | 13 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 3 |
| **Exit 39** | 0 | 0 | 14 | 0 | 2 | 0 | 1 | 161 | 0 | 21 | 81 |
| **Exit 40** | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Exit 41** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 |
| **Exit 43** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 |

In addition to the volume data from image processing, the research team gathered U-turn data using the manual data reduction technique. The U-turn data were collected for the east side U-turn since this site had two U-turn lanes. The drone view for the east side intersection is shown in Figure 68, and the collected U-turn data are shown in Table 24. Figure 68 also shows the lane number assigned to each lane. The research team collected the approach lane and departure lane for each of the turning vehicles. The reduced data included the number of vehicles that changed lanes during the U-turn maneuver. Lane changing was defined as crossing the dotted lane-line extension shown in Figure 68.

The U-turn at this location has two lanes (lane numbers 3 and 4 in Figure 68) and the receiving area also has two lanes (lanes 5 and 6) with the outer lane quickly splitting into two lanes (lanes 6 and 7). Lane 6, similar to Lane 5, is for traffic going straight, and Lane 7 is for traffic turning right. The preference is for those vehicles who are turning right to start in the outer U-turn lane (Lane 3) so that they are in position to easily move into the exclusive right-turn lane. Of the 445 vehicles observed, 61 vehicles (13 percent) changed lanes during the U-turn maneuver. Most of those changing lanes started in Lane 4 (the U-turn lane next to the median) and moved into Lane 6. None of the observed heavy trucks changed lanes.


**Figure 68. Lane Numbers for the East Side U-turn at Sardis Church Road Site.**

**Table 24. U-Turn Behavior for the East Double U-Turn Lanes at Sardis Church Road Site.**

| Changed Lane? | Approach Lane | Departure Lane | Vehicle Type | | Grand Total |
|---|---|---|---|---|---|
| | | | Truck | Passenger Car | |
| No | 3 | 5 | 1 | 2 | 3 |
| | | 6 | 6 | 111 | 117 |
| | | 7 | 0 | 119 | 119 |
| | 4 | 5 | 0 | 142 | 142 |
| | | 6 | 0 | 2 | 2 |
| | | 7 | 0 | 1 | 1 |
| No Total | | | 7 | 377 | 384 |
| Yes | 3 | 5 | 0 | 1 | 1 |
| | | 6 | 0 | 1 | 1 |
| | 4 | 5 | 0 | 3 | 3 |
| | | 6 | 0 | 46 | 46 |
| | | 7 | 0 | 10 | 10 |
| Yes Total | | | 0 | 61 | 61 |
| Grand Total | | | 7 | 438 | 445 |

*NC-IT: US 74 and Faith Church Road*

The data for the Faith Church Road site were collected per movement groups. The movement group names are shown in Figure 69. Since there were two cameras, highway through movements were captured and counted in both views; the intersection volume can highly affect the highway through volumes, and the volumes captured in the two cameras for the highway through movements do not necessarily need to be equal. Figure 70 shows volumes for each movement group by vehicle type.


Source: Base image from Google Earth.

**Figure 69. Movement Groups at Faith Church Road Site.**

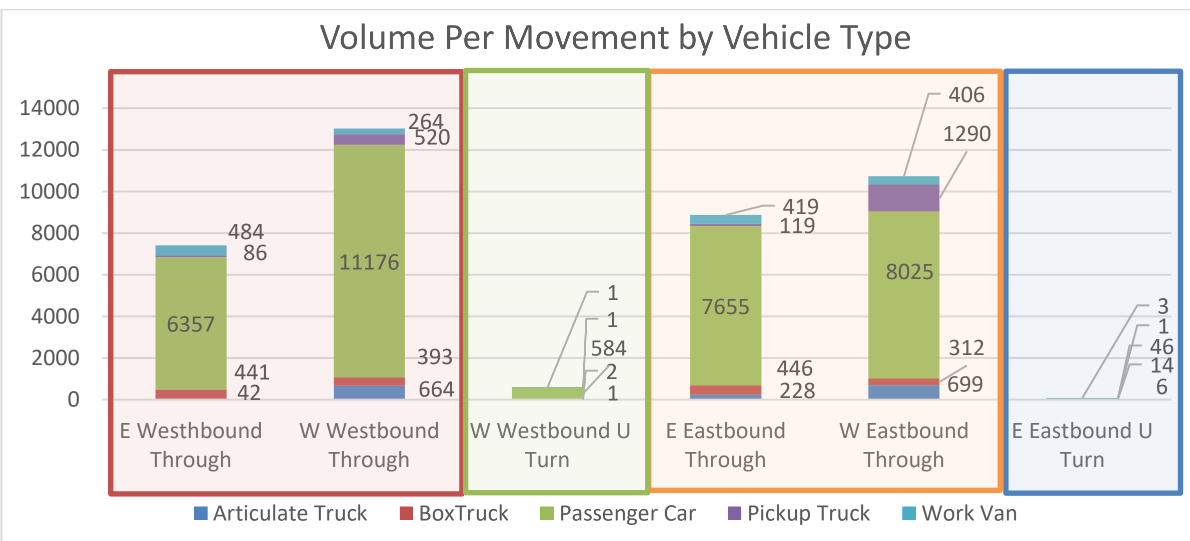



**Figure 70. Movement Group Volumes by Vehicle Type.**

The west side of the corridor carried heavier traffic compared to the east side. In addition, a larger number of the vehicles made a U-turn at the west side of the intersection. Although there was only one U-turn lane at both sides of the main intersection, the length of the exclusive U-turn lane on the west side was roughly twice as much as the length of the U-turn on the east side of the intersection (about 600 ft on the west side versus about 300 ft on the east side).

Table 25 shows the percentage of vehicles that made a U-turn compared to all vehicles going through on the same segment. Slightly more than 4 percent of the westbound traffic made U-turns compared to less than 1 percent of the eastbound traffic.

**Table 25. Proportion of U-Turning Vehicles at Each U-Turn.**

| Movement | Articulate Truck | Box Truck | Passenger Car | Pickup Truck | Work Van | Grand Total |
|---|---|---|---|---|---|---|
| W-WB-Th | 664 | 393 | 11176 | 520 | 264 | 13017 |
| W-WB-U | 1 | 2 | 584 | 1 | 1 | 589 |
| Ratio (%) | 0.15 | 0.51 | 4.97 | 0.19 | 0.38 | 4.33 |
| E-EB-Th | 228 | 446 | 7655 | 119 | 419 | 8867 |
| E-EB-U | 6 | 14 | 46 | 1 | 3 | 70 |
| Ratio (%) | 2.56 | 3.04 | 0.60 | 0.83 | 0.71 | 0.78 |

## SIMULATION

The research team used the PTV VISSIM simulation software to construct simulation models. The initial simulation model was built using the Sardis Church site geometries as gathered from aerial photographs. The signal timings were provided by the state, and the volumes and trip distribution were according to the available O-D matrix. The initial base model is shown in Figure 71.

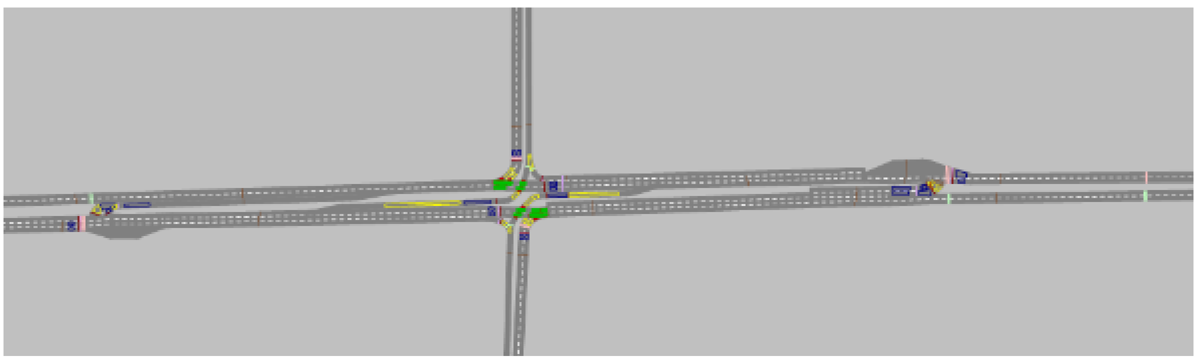


**Figure 71. Initial Base VISSIM Model.**

### Parameters Settings for PTV VISSIM Software

Although the VISSIM software is a strong and well-supported traffic simulation software, the research team took a deeper look into some base parameters that are used as default values in VISSIM. This step was taken to ensure that the VISSIM software reflected the standards and specifications of the site-specific cars and driving behaviors.

PTV VISSIM's default values incorporate normal driving conditions but they can be modified for each model. Some of the default values such as vehicle size, speed distribution, and driver behavior are set up for European driving conditions, and the research team modified those to represent U.S. conditions. Table 26 shows a list of variables that the research team modified while building the simulation model. The following section provides additional explanation for the speed and vehicle size parameters in Table 26 along with details on how the simulation model was validated.

**Table 26. Proposed List of Calibration Variables.**

| Parent Parameter | Parameter | Default Value | Proposed Value |
|---|---|---|---|
| **Desired Speed** Distribution | For 45 mph (70 km/h) | Diagram | Modify to S-shaped curve |
| **Vehicle Size** Distribution Elements | For vehicle type 10: Car | European cars | American cars |
| **Driving Behavior**—Urban (motorized)—Following | Look ahead distance-Minimum | 0 | > 0[1] |
| **Driving Behavior—**Lane Change | Necessary lane change—Maximum deceleration—Own | −13.12 ft/s2 | −11.2 ft/s2 [2] |
| **Driving Behavior—**Lane Change | Cooperative lane change | Un-checked | Check |

*Note:* [1] *"If several vehicles can overtake within a lane, this value needs to be greater than 0.00, e.g., in urban areas, depending on the speed, the look ahead distance might be approx. 20–30m, with correspondingly larger values for outside of the city."* https://cgi.ptvgroup.com/vision-help/VISSIM_2021_ENG/Content/4_BasisdatenSim/FahrverhaltensparameterFolgeverhalten.htm
[2] *Green Book (27), Stopping Sight Distance "a" value.*

*Speed*

Desired speeds in VISSIM represent a range of speed values with the speed being assigned to each vehicle or pedestrian from within that range. The nominal range of desired speeds can be modified in the VISSIM window, as shown in Figure 72.

Several simulation components have a speed parameter including:

- Zone connectors in the dynamic assignment setting.
- Desired speed decisions that change the speed of the vehicles on the link for the rest of the link they are placed on.
- Reduced speed areas that change the speed of the vehicles in a small area of the network, such as turn areas.
- Upcoming traffic speed that is used when modeling two opposing directions of travel without physical barriers and allowing overpasses.

VISSIM's default speed distributions are linear (see example in Figure 72), while in practice the speed distributions follow a S-shaped curve. The research team modified the desired speed distribution curve as shown in Figure 73.

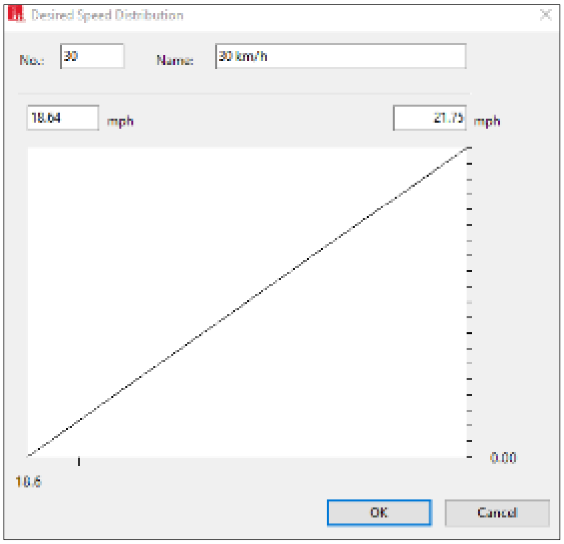



Figure 72. Example of a VISSIM Desired Linear Speed Distribution Graph for 18.64 to 21.75 mph.

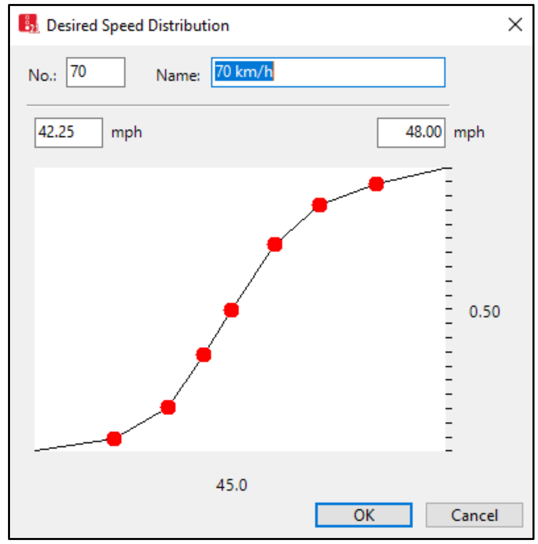



Figure 73. Adjusted Desired Speed Distribution Curve for the Range of 42.25 to 48 mph.

*Vehicle Size*

Each vehicle type consists of several specific vehicle sizes and dimensions based on real-world car measurement. Figure 74 shows the vehicle type “10: Car” consists of 7 vehicles. VISSIM has the capability of modifying the combinations. In addition to being able to import 3D models, VISSIM has the capability of changing vehicle dimensions and other parameters in the “Edit 2D/3D” menu, as shown in Figure 75.

A recent study by IHS Markit shows that cars in the United States stay on the road for an average of 11.8 years (120). The research team acquired car production data from for the 2008–2019 period from the Environmental Protection Agency (EPA) and used that to adjust the vehicle type distribution in the VISSIM model. EPA classifies passenger vehicles (light duty cars) into five major classes including:

- Car sport utility vehicle (SUV).
- Minivan/Van.
- Pickup.
- Sedan/Wagon.
- Truck SUV.

The EPA classifies pickup trucks, vans, and minivans as trucks, while sedans, coupes, and smaller vehicles are classified as cars. SUVs are classified based on weight and power distribution attributes. SUVs that weigh less than 6,000 lbs gross vehicle weight and are two-wheel-drive are classified as cars, while others are classified as trucks (*121*).

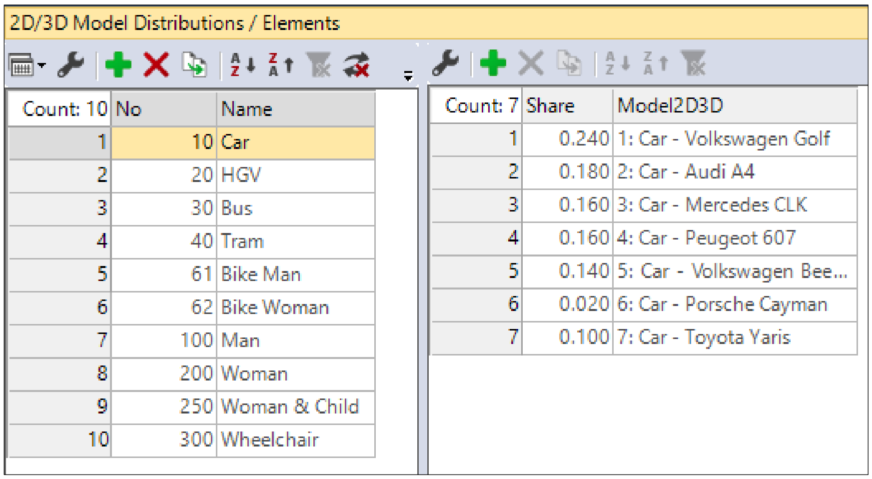



**Figure 74. Vehicle Type Model Distribution for Vehicle Type "Car."**

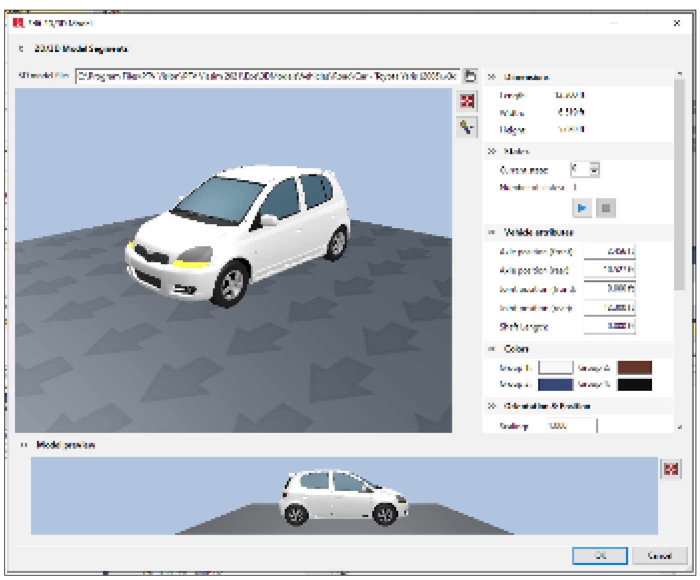


**Figure 75. Expanded 2D/3D Model Characteristics of Toyota Yaris 2006.**

Table 27 shows vehicle production shares for 2008–2019. The average of the 12-year period has been used in the simulation models.

**Table 27. Car Production Shares for 2008–2019.**

| Year | Car SUV | Minivan/Van | Pickup | Sedan/Wagon | Truck SUV | Grand Total |
|---|---|---|---|---|---|---|
| | ***Toyota RAV4*** | ***Chrysler Voyager*** | ***Ford F150*** | ***Honda Accord*** | ***Toyota Rav4*** | |
| 2008 | 0.07 | 0.06 | 0.13 | 0.53 | 0.22 | 1.00 |
| 2009 | 0.07 | 0.04 | 0.11 | 0.61 | 0.18 | 1.00 |
| 2010 | 0.08 | 0.05 | 0.11 | 0.55 | 0.21 | 1.00 |
| 2011 | 0.10 | 0.04 | 0.12 | 0.48 | 0.26 | 1.00 |
| 2012 | 0.09 | 0.05 | 0.10 | 0.55 | 0.21 | 1.00 |
| 2013 | 0.10 | 0.04 | 0.10 | 0.54 | 0.22 | 1.00 |
| 2014 | 0.10 | 0.04 | 0.12 | 0.49 | 0.24 | 1.00 |
| 2015 | 0.10 | 0.04 | 0.11 | 0.47 | 0.28 | 1.00 |
| 2016 | 0.11 | 0.04 | 0.12 | 0.44 | 0.29 | 1.00 |
| 2017 | 0.12 | 0.04 | 0.12 | 0.41 | 0.32 | 1.00 |
| 2018 | 0.11 | 0.03 | 0.14 | 0.37 | 0.35 | 1.00 |
| 2019 | 0.12 | 0.03 | 0.16 | 0.33 | 0.37 | 1.00 |
| Average | 0.10 | 0.04 | 0.12 | 0.48 | 0.26 | 1.00 |

Source: EPA.

The research team selected the following cars as representatives for each vehicle class and applied the respective market share in the simulation models:

- Car SUV—Toyota RAV4.
- Minivan/Van—Nissan Quest.
- Pickup—Ford F150.
- Sedan/Wagon—Honda Accord.
- Truck SUV—Toyota RAV4.

The final vehicle shares for the various vehicle classes are shown in Table 28.

**Table 28. Vehicle Shares in VISSIM Models.**

| Vehicle Type | Percentage |
|---|---|
| 310: Sedan/Wagon—Honda Accord | 10 |
| 303: Minivan/Van—Nissan Quest | 4 |
| 304: Pickup—Ford F150 | 12 |
| 302: Car SUV—Toyota RAV4 | 48 |
| 308: Truck SUV—Toyota RAV4 | 26 |

For heavy vehicles, VISSIM adjusts acceleration based on power and weight distribution. The overall truck percentage was based on the review of statewide truck percentages on rural two-lane highways in Texas, which ranged between 10 and 35 percent with an average of 22 percent (*122*). To further subset the trucks, the research team adopted a procedure developed by WisDOT (*123*), which assumes a 75/25 split between single-unit and tractor-trailer truck types.

The Wisconsin procedure classifies trucks into smaller and larger trucks and recommends having three vehicle classes in the simulation models, namely cars, single-unit trucks, and tractor-trailers. The final vehicle compositions are shown in Table 29.

**Table 29. Vehicle Compositions.**

| **Distribution** | **Vehicle Type** | **Composition 1** | **Composition 2** | **Composition 3** |
|---|---|---|---|---|
| Initial | Car | 0.9 | 0.78 | 0.65 |
| Initial | Truck | 0.1 | 0.22 | 0.35 |
| **Additional split by truck type** | | | | |
| Used in simulation | Car | 0.9 | 0.78 | 0.65 |
| Used in simulation | Single Unit | 0.075 | 0.165 | 0.2625 |
| Used in simulation | Tractor Trailer | 0.025 | 0.055 | 0.0875 |

*Validating The Simulation Models*

The three steps of model building are verification, validation, and calibration:

- **Verification** is checking the underlying models such as driver behavior and mathematical relationships to make sure each component works well.
- **Validation** is comparing the model outputs to the real-world measurements to ensure the model creates results that are reasonably accurate. No model mimics the real world completely. Thus, each simulation model should have a validation parameter to compare the real-world observations to model outputs.
- **Calibration** is the modification and adjustment of simulation parameters such that the simulation models provide results that mimic the real world more closely. Calibration is done after validation, if needed.

After updating the default values to the recommended values, the research team validated the model using travel time. Travel time is a widely used performance measure for validation since it is easy to measure and can be used to derive other performance measures like delay. Figure 76 shows the zone numbers for the created simulation models where the green lines represent the points on the segments where the travel times were measured to/from. The research team ran the base simulation model five times and compared the observed travel time values to the simulation output values using confidence interval testing. Table 30 shows the travel time matrix observed at the study site, the travel time matrix measured from the simulation model, and the percent difference between the two.

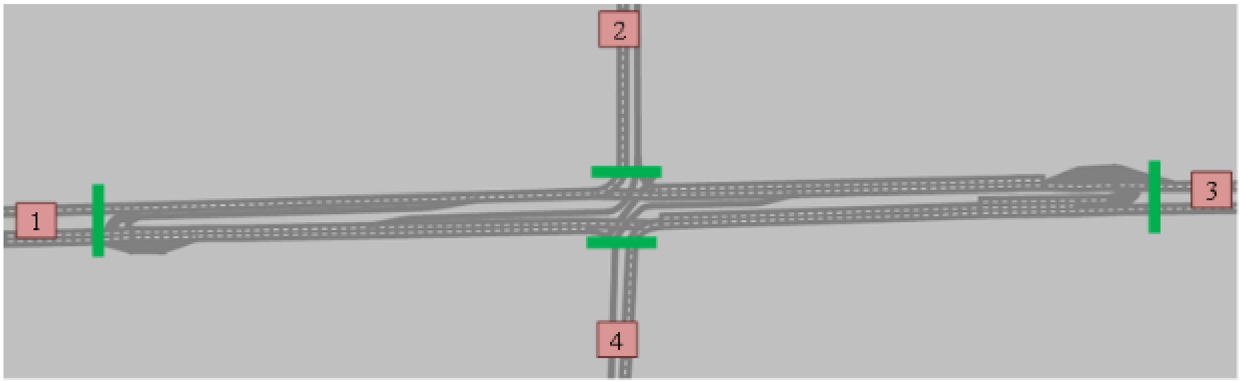



**Figure 76. Simulation Model Travel Time Segments with Zone Numbers at Edges of Roads and Segment Numbers within the Segments.**

**Table 30. Observed Travel Time Matrix, Simulated Travel Time Matrix, and Percent Difference.**

| Observed (sec) | Zone | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| | 1 | 0 | 49 | 35 | 21 |
| | 2 | 24 | 0 | 116 | 126 |
| | 3 | 31 | 23 | 0 | 74 |
| | 4 | 94 | 76 | 19 | 0 |
| | | | | | |
| Simulation (sec) | Zone | 1 | 2 | 3 | 4 |
| | 1 | — | 43.41 | 34.18 | 21.20 |
| | 2 | 21.53 | — | 83.80 | 70.44 |
| | 3 | 36.73 | 22.93 | — | 45.15 |
| | 4 | 93.18 | 72.17 | 18.66 | — |
| | | | | | |
| Difference (%) | Zone | 1 | 2 | 3 | 4 |
| | 1 | — | −11.41 | −2.34 | 0.95 |
| | 2 | −10.27 | — | −27.76 | −44.09 |
| | 3 | 18.47 | −0.32 | — | −38.98 |
| | 4 | −0.87 | −5.04 | −1.78 | — |

*Note: — = not applicable.*

Three of the 12 measurements of the difference between observed and simulated travel time were outside of the 20 percent acceptable error range. A further look into the observed measurements shows that the travel time from Zone 2 to Zone 3 is equal to 116 seconds, while the travel time from Zone 2 to Zone 4 is observed to be 126 seconds even though the distance between Zones 2 and 3 is longer. On the other hand, the simulation travel times yield roughly equal values for travel time 2 to 4 and 4 to 2, while the observed values do not. The research team concluded that the observed travel times for Zone 2 to 3 and Zone 2 to 4 do not represent normal situations, and they assumed that the simulation model better represented typical conditions. Another out-of-range observation was the travel time from Zone 3 to 4, where the simulated travel time was 38 percent lower than the observed values. A closer look shows that travel time for Zone 1 to 2 and Zone 3 to 4 should be close in value, which is true in the simulation model but not true in the observed values. Similar to Zone 2 to 3 and Zone 2 to 4, the research team decided to accept the simulated model for Zone 3 to 4.

## Scenario Management

The research team created the following base models to investigate the effects of the distances between the main intersection and the neighboring U-turns:

- No RCUT, 425 ft, 700 ft, 1,000 ft, 1,500 ft, and 2,000 ft.

The following parameters were modified to create different scenarios for each of the six base models: major road volume, minor road volume, left-turn percent, and truck percent. The range for these parameters were:

- Major road volume (vpd): 10,000, 15,000, and 20,000.
- Minor road volume (vpd): 2,000, 4,000, 6,000, 8,000, 10,000, 12,000, and 14,000.
- Left-turn percent: 10, 20 or 30 percent.
- Truck percent: 5, 22, or 35 percent, or heavy truck percent: 2.5, 5.5, or 8.75 percent.

Moreover, the following conditions were used throughout the study:

- Major road split: 60/40 (suitable for the 4-hour simulation period).
- Minor road split: 50/50.
- Major road right-turn lane volume: equal to left-turn volume.

### *Determining the Number of Runs*

Simulation models are based on stochastic models that use random number generators. To account for possible errors caused by random numbers, simulation models are usually run several times. Determining the number of runs becomes important when the models use calculation resources and times intensively; running too many simulations would waste time and resources. The number of runs can be determined based on the desired level of precision (margin of error) and the standard deviation of the observed measure of effectiveness:

$$n = \left(\frac{Z * SD}{E}\right)^2$$

Where:

N = number of runs.

Z = the Z value for the desired confidence level (1.96 for 95 percent confidence level).

SD = the standard deviation of the observed values.

E = the acceptable margin of error.

Table 31 shows the standard deviation values for all travel time values from the simulation models. The average SD value for these measurements is 4.068, and the research team chose 5 seconds as the acceptable margin of error. Based on these values, the minimum sample size is equal to three. The research team chose to run each scenario three times.

$$n = \left(\frac{1.96 * 4.068}{5}\right)^2 = 2.96 \approx 3$$

**Table 31. Standard Deviation Values for Simulated Travel Times.**

| Zone | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | — | 3.706 | 0.984 | 1.225 |
| 2 | 0.216 | — | 2.776 | 13.921 |
| 3 | 2.057 | 1.728 | — | 5.378 |
| 4 | 4.577 | 11.306 | 0.947 | — |

*Note: — = not applicable.*

*Running Simulation Models for Different Scenarios*

The research team decided to conduct a full factorial simulation, meaning that all combinations of the different options for all variables were studied. In this study, the factorial method yielded three major road volumes, seven minor road volumes, three left-turn percentages, and three truck percentages for 189 scenarios (3 × 7 × 3 × 3). Running each scenario three times resulted in 567 runs (3 × 189). To better manage the runs, the research team used the validated model to produce the six base models for the different U-turn distance options and then used a computer program to automate scenario creation and VISSIM runs. Figure 77 and Figure 78 show two of the models at the same time point for scenario 189. The figures show that the 425-ft model experienced obvious congestion with the shorter distance between the main intersection and the U-turn lanes, but the 1,000-ft model performed significantly better.

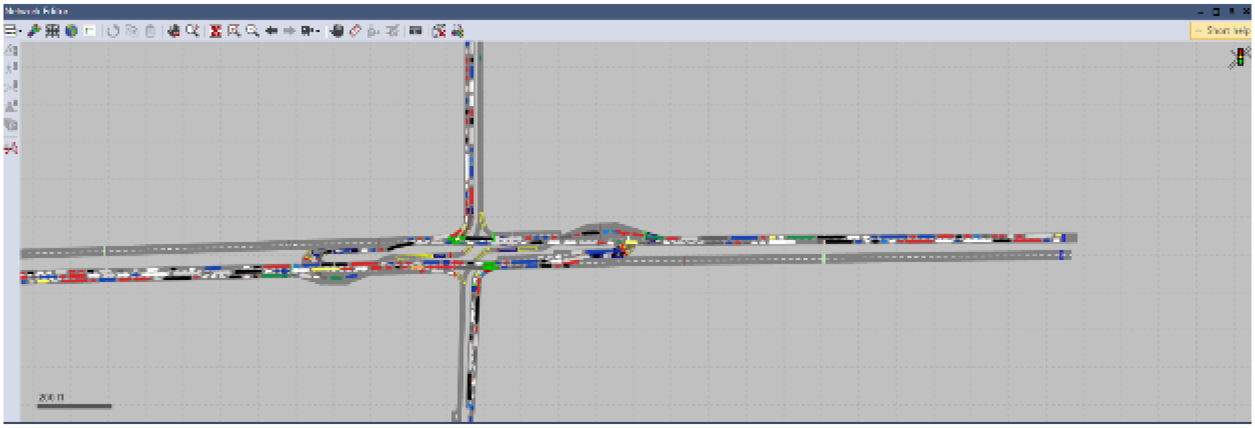


**Figure 77. VISSIM Model for 425-ft Distance Option at 1:07:40.**

**Figure 78. VISSIM Model for 1,000-ft Distance Option at 1:07:09.**

### Simulation Results

The research team chose a factorial sampling method to build different scenarios and investigated all possible combinations of different options for study parameters. Six base simulation models were built to represent the spacing between the main intersection and the U-turn. The spacing between the main intersection and the U-turn lane was either 425 ft, 700 ft, 1,000 ft, 1,500 ft, or 2,000 ft. In addition, a model was created to represent the no RCUT condition and was assigned a distance of 0 ft for managing the output data.

The range of major volume, minor volume, left-turn percent, and truck percent led to 189 different simulation runs for each of the six different U-turn lengths. Within each run, data were collected for 12 paths of interest (see Figure 79 and Table 32). With running each combination three times, 40,824 (6 models × 189 scenarios × 12 paths × 3 runs per scenario) runs or rows of output data (e.g., travel time, volume, speed, etc.) were generated.

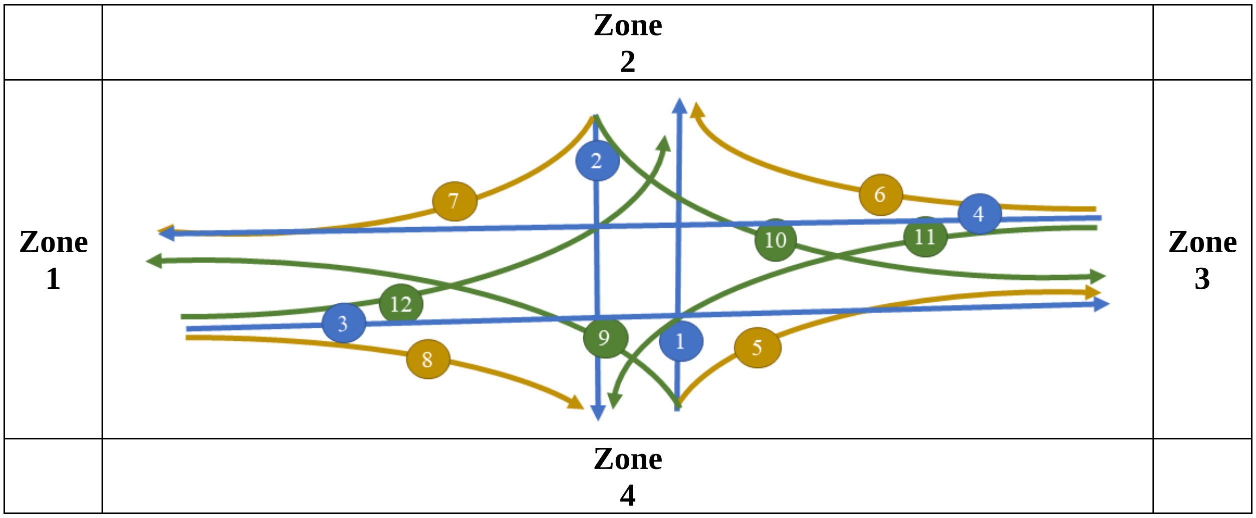


**Figure 79. Paths.**

**Table 32. Path Characteristics.**

| Path | From Road | From Leg | To Leg | Movement |
|---|---|---|---|---|
| 1 | Minor | South | North | Through |
| 2 | Minor | North | South | Through |
| 3 | Major | West | East | Through |
| 4 | Major | East | West | Through |
| 5 | Minor | South | East | Right |
| 6 | Minor | East | North | Right |
| 7 | Major | North | West | Right |
| 8 | Major | West | South | Right |
| 9 | Minor | South | West | Left |
| 10 | Minor | North | East | Left |
| 11 | Major | East | South | Left |
| 12 | Major | West | North | Left |

To conduct the analysis, a database was built by compiling the following:

- Scenario characteristics.
- Travel time data and distance traveled data, which were used to create the speed for each path.
- Vehicle volume.

VISSIM was set to save a “Vehicle Record” file for each of the simulation runs. A program in the R coding environment was developed to read each of the files and extract the real volumes data for each of the links that would be included in the final database. Table 33 shows the variables in the final database with their definitions.

**Table 33. Final Database Variables.**

| Variable Name | Definition |
|---|---|
| Distance | U-turn distance |
| SimRun | Simulation run number |
| From | Evaluation start time |
| To | Evaluation end time |
| Path | Travel time measurement segment name |
| VEHS(ALL) | Count of all vehicles that completed the path |
| VEHS(10) | Count of cars that completed the path |
| VEHS(70) | Count of single unit heavy trucks that completed the path |
| VEHS(80) | Count of tractor trailers that completed the path |
| TRAVTM(ALL) | Average travel time for all vehicles |
| TRAVTM(10) | Average travel time for cars |
| TRAVTM(70) | Average travel time for single unit trucks |
| TRAVTM(80) | Average travel time for tractor trailers |
| DISTTRAV(ALL) | Average travel distance for all vehicles in the path |
| DISTTRAV(10) | Average travel time for cars in the path |
| DISTTRAV(70) | Average travel time for single unit trucks in the path |
| DISTTRAV(80) | Average travel time for tractor trailers in the path |
| Speed(all) | Average speed for all vehicles |
| Speed(10) | Average speed for cars |
| Speed(70) | Average speed for single unit trucks |
| Speed(80) | Average speed for tractor trailers |
| Vol_Demand | Volume that was assigned to the path at the start of the simulation |
| %onPath | Percent of volume that was actually simulated and run in the model |
| Major | Nominal major road vehicle input* |
| Left Turn | Nominal left turn percentage (equals right turn percentage)* |
| Minor | Nominal minor road vehicle input* |
| Truck | Nominal truck percentage* |

*Note: * Nominal means this value was used to create the scenarios and the actual simulated values might differ from them.*

After compiling the database, the data were analyzed. The analysis included the following traffic measures:

- Travel time.
- Speed (calculated from travel time and distance).

*Travel Time Analysis*

The compiled database included travel time data for passenger cars, single-unit trucks, and tractor-trailer vehicles as well as a weighted average travel time for all vehicles. The research team decided to focus on the weighted average travel time data for further study. In some cases, travel time values were not available. Most of these cases were associated with either the model with 425-ft spacing or the model without the RCUT design. The volumes selected for this evaluation included very high major and minor road volumes to see when the network was operating poorly, so it was not surprising that cases where vehicles were essentially not moving through the system were captured (see example provided in Figure 77). Approximately 22 percent of the 425-ft spacing and 15 percent of the no RCUT model did not have travel times. These runs were identified as missing data and were not included in the analyses.

*Speed Analysis for Key Variables*

Speeds were averaged by different combinations of the factors to identify which variables are more influential. Figure 80 shows the average speed for all combinations by path and the major road vehicle volumes used in the simulation. As expected, the average speed for each path decreased with increasing major road volume. Similar trends are also present when the minor road vehicle volume increased, when the percent trucks increased, and when the left-turn percent increased. As expected, speeds decreased as vehicle volume on either the major or the minor road increased.

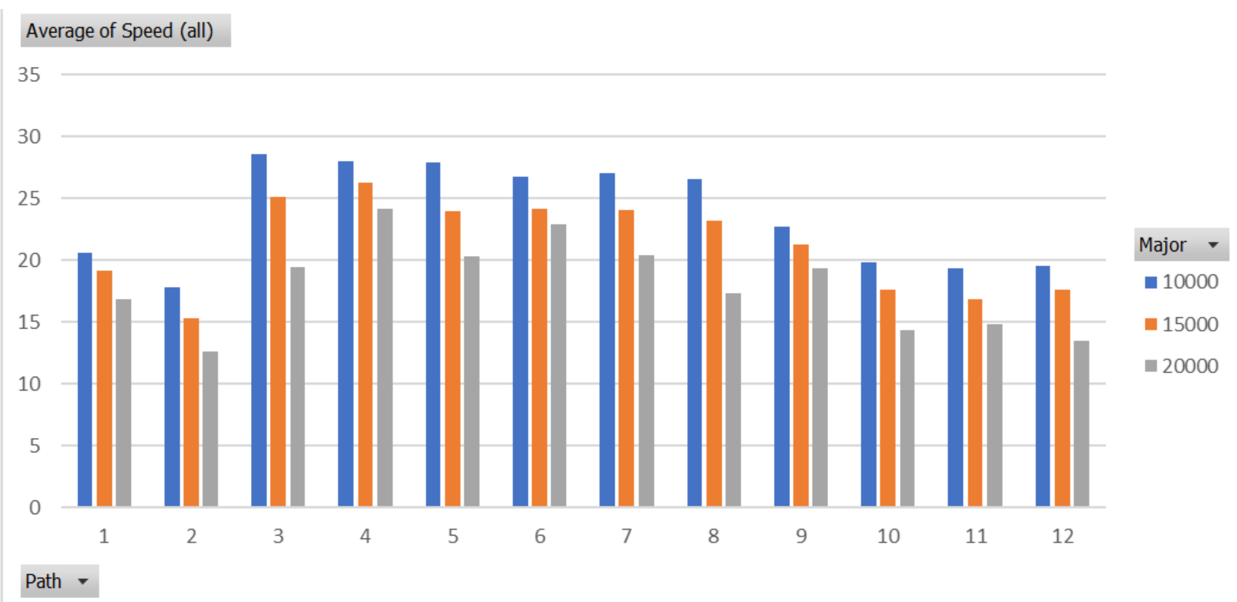



**Figure 80. Average Speed by Path and Major Road Vehicle Volume.**

*Speed Analysis for Spacing to U-Turn Lanes*

An initial review of the average speed by distance between the main intersection and the U-turn can be seen in Figure 81. The results show that overall the average speed increases with greater distance between the main intersection and the U-turn intersection. The highest average speed was identified for the 2,000-ft distance between the main and U-turn intersections. The figure also shows that having the U-turn intersection only 425 ft downstream from the main intersection results in poorer performance as compared to a conventional signalized intersection.

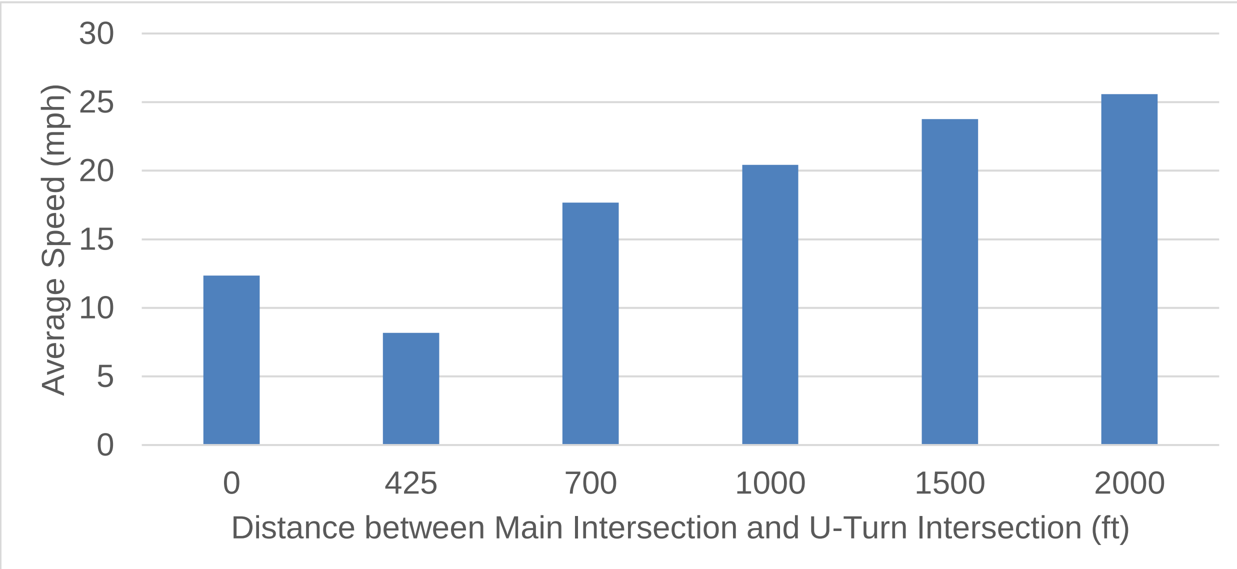



**Figure 81. Overall Average Speed by Distance between Main Intersection and U-turn Intersection.**

The graph in Figure 82 provides a closer look at the average speeds by path and by distance between intersections for the left turns. Paths 9 and 10 represents the left turns from the minor road, while paths 11 and 12 are from the major road. An advantage of the RCUT is in how it manages left-turning vehicles. As illustrated in Figure 82, the left turns from the minor road (paths 9 and 10) improve with the conversion from a signalized intersection to an RCUT regardless of the distance between the intersections; however, the benefits are minor for the shortest distance considered (425 ft) but have similar speeds as experienced by the major street left-turning driving when the distance is 700 ft and greater. The data for paths 11 and 12 demonstrate that the distance between the intersections needs to be at least 700 ft or more and preferably 1,500 ft or more for the major road drivers to have similar operating speeds for the RCUT as compared to a conventional signalized intersection. The 2,000-ft distance between the main intersection and the U-turn intersection resulted in the highest speeds for the simulated corridors.

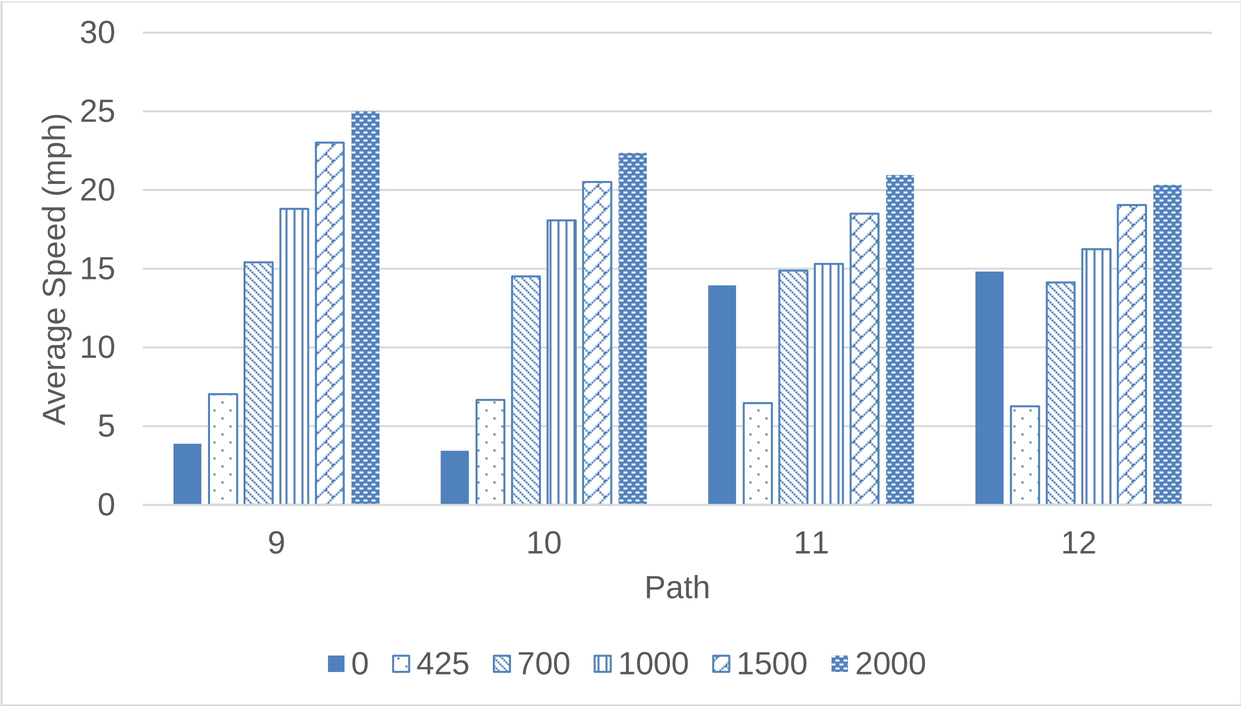



**Figure 82. Average Speed by Path and Distance between Main Intersection and U-Turn Intersection (ft).**

# CHAPTER 6: INNOVATIVE INTERSECTION SAFETY REVIEW

## INTRODUCTION

This chapter documents the safety analysis conducted in this project. The research team obtained crash data on Texas innovative intersection locations to identify crash patterns and trends associated with those features.

## METHODOLOGY

The FHWA project *Field Evaluation of At-Grade Alternative Intersection Designs* (*124*) will contain a comprehensive safety evaluation that will include available Texas sites. To avoid duplicating efforts, and in recognition of the limited number of existing sites in Texas, the research team focused project 0-7036 on reviewing crash details at innovative intersections in Texas. The research team queried the Crash Record Information System (CRIS) database and identified crashes at and near the identified innovative intersections. The research team reviewed the CRIS codes to determine where the crash occurred within the boundary area of the innovative intersection. Based upon available details, the research team determined conflict areas within the innovative intersection boundaries and investigated if or how specific features of the innovative intersection are associated with the crashes.

## DATA COLLECTION

### Identifying Innovative Intersections

Innovative intersections installed in Texas were identified through the existing knowledge of the research team and feedback from TxDOT and professional associates. The research team also searched the local media and news articles to identify the innovative intersections installed in Texas as well as their installation dates.

A total of 14 sites were considered in the safety study. These include five DDIs, six DLTs, two MUTs, and one RCUT. The construction period for these intersections was estimated using online news articles, construction crash codes in the crash database, and estimated typical construction period length. Table 34 depicts the list of the intersections and cities as well as the name of the main and cross streets and construction end date.

**Table 34. List of Innovative Intersections Selected.**

| Intersection Type | Intersection ID | City | Main Road Name | Cross Street Name | End Construction |
|---|---|---|---|---|---|
| Diverging Diamond Interchange | DDI_AU | Round Rock | MoPac Service Road | Slaughter Ln | 2/15/2019 |
| | DDI_CS | College Station | FM 60 | FM 2818 | 5/1/2019 |
| | DDI_EP | El Paso | SH 375 | SH 601 | 9/1/2014 |
| | DDI_RR1 | Round Rock | IH-35 Frontage Road | FM 1431 | 12/10/2015 |
| | DDI_TC | The Colony | SH-121 | S Colony Blvd | 3/1/2016 |
| Displaced Left-Turn | DLT_AU1 | Austin | US-290 | SH 71 | 9/30/2014 |
| | DLT_AU2 | Austin | US-290 | William Cannon Dr | 9/16/2014 |
| | DLT_CP | Cedar Park | FM 1431 | Parmer Ln | 12/30/2016 |
| | DLT_SA | San Antonio | SH 16 | Loop 1604 | 7/3/2019 |
| | DLT_SM1 | San Marcos | IH-35 Frontage Road | Aquarena Springs Dr | 6/15/2014 |
| | DLT_SM2 | San Marcos | IH-35 Frontage Road | SH 80 | 9/1/2014 |
| Median U-Turn | MUT_AU | Austin | US-290 | Joe Tanner Ln | 8/1/2014 |
| | MUT_CS | College Station | SH 21 | Luza Ln | 9/1/2018 |
| Restricted Crossing U-Turn | RCUT_AU | Austin | SH 360 | Barton Creek Plz | 1/1/2017 |

## SETTING STUDY SITE LIMITS FOR CRASH SELECTION

Identifying the list of crashes related to the selected sites is not trivial, partly because the innovative intersections have very complex configurations, and determining whether the crash occurred due to these configurations is not straightforward. Another challenge is when roadway crashes are not assigned to the correct road. This is particularly the case for intersection and interchange crashes, where sometimes a crash taking place on a frontage road or ramp is assigned to the freeway. Another example that could affect the evaluation is if the vehicles were on the cross-street approach to the intersection and were assigned to the major road.

The research team implemented the following procedure to identify the crashes that occurred at or near the selected sites:

1. First, the "*boundary*" of the innovative intersection was determined based on its configuration. The procedure for determining the boundaries differed based on the intersection type and is explained in detail in the following sections.

2. Second, "*study limit"* was determined as the SSD value upstream of the boundary point. SSD is determined using the posted speed limit (PSL) of the roadway and is calculated by using the following equation:

$$SSD = 1.47 \cdot V \cdot t + 1.075 \cdot \frac{V^2}{a}$$

Where:

D = stopping sight distance (ft).
V = design speed or posted speed limit (mph).
t = brake reaction time (assumed to be 2.5 s) (s).
a = deceleration rate (ft/s).

Table 35 lists the SSD for different design speeds. The research team used the above equation and Table 35 to determine the SSD of main and cross streets for each intersection (see Table 36).

**Table 35. Stopping Sight Distance Values.**

| Design Speed (mph) | Brake Reaction Distance (ft) | Braking Distance on Level (ft) | SSD—Calculated (ft) | SSD—Design (ft) |
|---|---|---|---|---|
| 15 | 55.1 | 21.6 | 76.7 | 80 |
| 20 | 73.5 | 38.4 | 111.9 | 115 |
| 25 | 91.9 | 60.0 | 151.9 | 155 |
| 30 | 110.3 | 86.4 | 196.7 | 200 |
| 35 | 128.6 | 117.6 | 246.2 | 250 |
| 40 | 147.0 | 153.6 | 300.6 | 305 |
| 45 | 165.4 | 194.4 | 359.8 | 360 |
| 50 | 183.8 | 240.0 | 423.8 | 425 |
| 55 | 202.1 | 290.3 | 492.4 | 495 |
| 60 | 220.5 | 345.5 | 566.0 | 570 |
| 65 | 238.9 | 405.5 | 644.4 | 645 |
| 70 | 257.3 | 470.3 | 727.6 | 730 |
| 75 | 275.6 | 539.9 | 815.5 | 820 |
| 80 | 294.0 | 614.3 | 908.3 | 910 |
| 85 | 313.5 | 693.5 | 1007.0 | 1010 |

Source: Table 3-2, page 3–4 in *A Policy on Geometric Design of Highways and Streets* (Green Book), 7th Edition. (27).

**Table 36. Posted Speed Limit and Stopping Sight Distances.**

| Intersection ID | Posted Speed Limit (mph) | | Stopping Sight Distance (ft) | |
|---|---|---|---|---|
| | Main Road | Cross Street | Main Road | Cross Street |
| DDI_AU | 65 | 30 | 645 | 200 |
| DDI_CLL | 55 | 45 | 495 | 360 |
| DDI_EP | 45 | 50 | 360 | 425 |
| DDI_RR1 | 60 | 45 | 570 | 360 |
| DDI_TC | 55 | 45 | 495 | 360 |
| DLT_AU1 | 45 | 45 | 360 | 360 |
| DLT_AU2 | 45 | 45 | 360 | 360 |
| DLT_CP | 60 | 60 | 570 | 570 |
| DLT_SA | 45 | 45 | 360 | 360 |
| DLT_SM1 | 45 | 35 | 360 | 250 |
| DLT_SM2 | 45 | 35 | 360 | 250 |
| MUT_AU | 45 | 30 | 360 | 200 |
| MUT_CLL | 65 | 30 | 645 | 200 |
| RCUT_AU | 55 | 15 | 495 | 80 |

### Diverging Diamond Interchange

For the DDI intersections, the study boundary was assumed to be the merging and diverging points. The diverge point is defined as being the location when a white lane line begins that separates the two lanes. The merge point is defined as being the location where the ramp is no longer separated from the main road by more than a lane line. For example, in a parallel ramp design, the location where the white edge line for the main road meets the ramp's white edge line is defined as the point of merge. While the white solid edge line communicates to motorists to not cross, motorists are physically able to cross the marked line. While motorists can also cross the space upstream of that merge point because the space between the converging lines is flush, the decision was made to have the merge point be the location where the two white edge lines meet.

The diverge point is defined as being the location when a white lane line begins that separates the two lanes. The study boundary was then assumed to be the farthest diverge and merge point from the intersection. The pins D and M in Figure 83 illustrate the merge and diverge points for a DDI. This figure shows the pins selected for determining the boundaries of the DDI in Round Rock (DDI_RR). Note that pins also show the direction of traffic (northbound [NB], southbound [SB], westbound [WB] and eastbound [EB]). The SSD of 645 and 425 ft are applied from the boundary points to determine the study limits for main and cross streets, respectively (cyan pins). The study limits are used to identify potential crashes associated with the DDI.

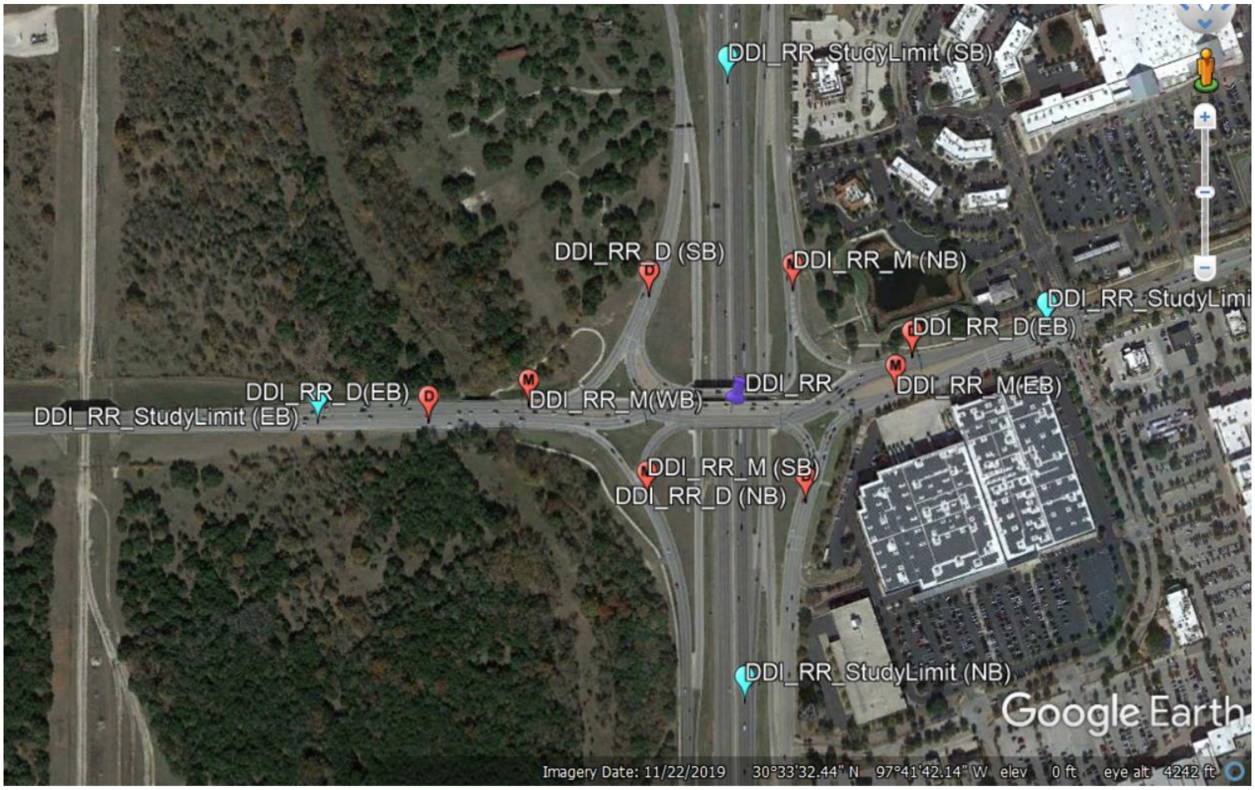



**Figure 83. Determining Limits for DDI.**

**Displaced Left Turn**

To capture crashes that may reflect lane changes on the approach to a DLT, the boundary was set at the point when the DLT lane was full width, which would be at the end of the DLT lane taper. The study limit was then determined using the SSD value of the corresponding street upstream of that boundary point, unless that distance would capture another intersection, in which case the study limit was set at the point where the stop bar occurred for the opposing direction of travel. For example, in Figure 84, the SSD for determining the study limits on the main road was 570 ft upstream of the displaced left-turn (illustrated using T pin), however, due to another intersection in northbound direction, the distance between the turn lane and the study limit was set to be 352 ft. The SSD for determining the study limits on the cross street was equal to 570 ft.

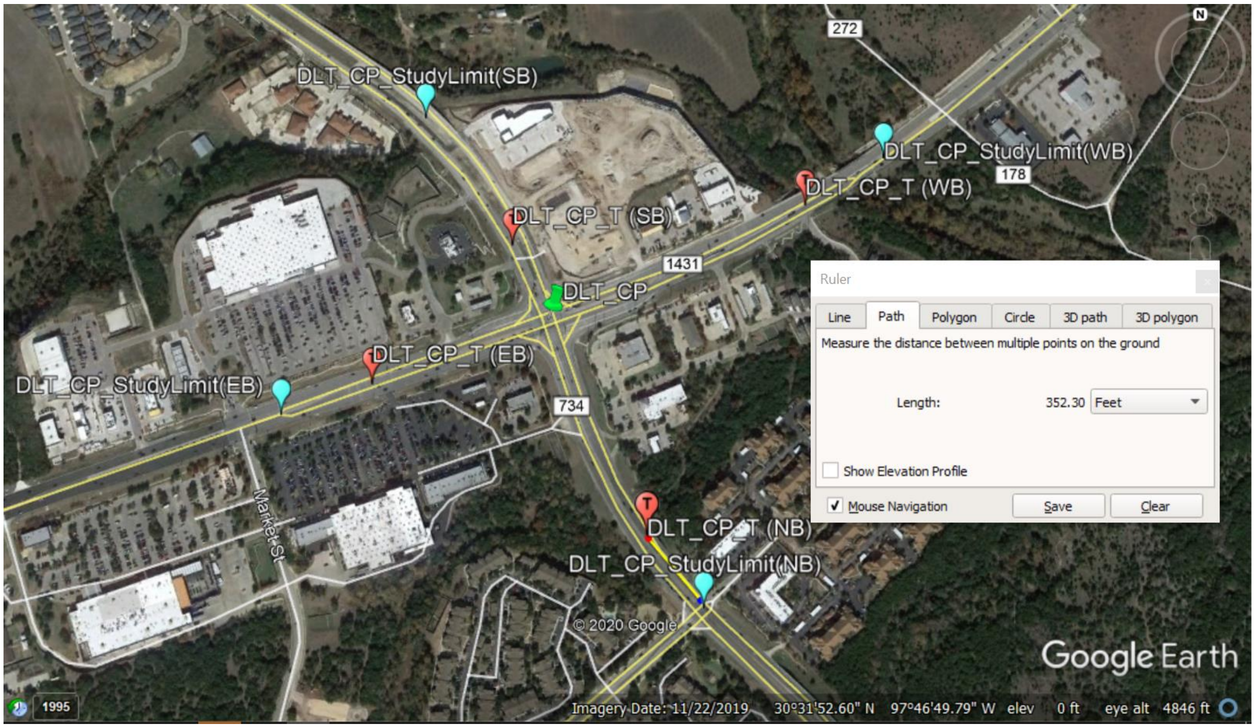



**Figure 84. Determining Limits for DLT.**

## Median U-Turn

The boundary for the MUT configuration was set at the point where the U-turn lane was full width and the stop bar of the signalized intersection. The study limits then used the SSD value for main and cross streets upstream of these boundaries. The study limits of MUT in Austin (MUT_AU) are illustrated in Figure 85. The study limits were located 300 ft upstream of the U-turn lane (U pin) and stop bar (square in red pin) for this intersection.


**Figure 85. Determining Limits for MUT.**

### Restricted Crossing U-Turn

Like MUT, the southbound boundary for the RCUT was set at the stop bar on the U-turn or loon approach. Figure 86 shows the limits for the RCUT in Austin (RCUT_AU), where the main intersection has three legs, and the U-turn has just the two approaches. The RCUT_AU site has a loon at the U-turn (L pin) to provide additional space for turning vehicles, especially large vehicles. The study limit on the northbound direction was set 495 ft upstream of the stop bar on the main intersection's south leg. Due to another intersection, the study limit for the southbound direction (north leg) was set at 495 ft upstream of the stop bar at the U-turn.

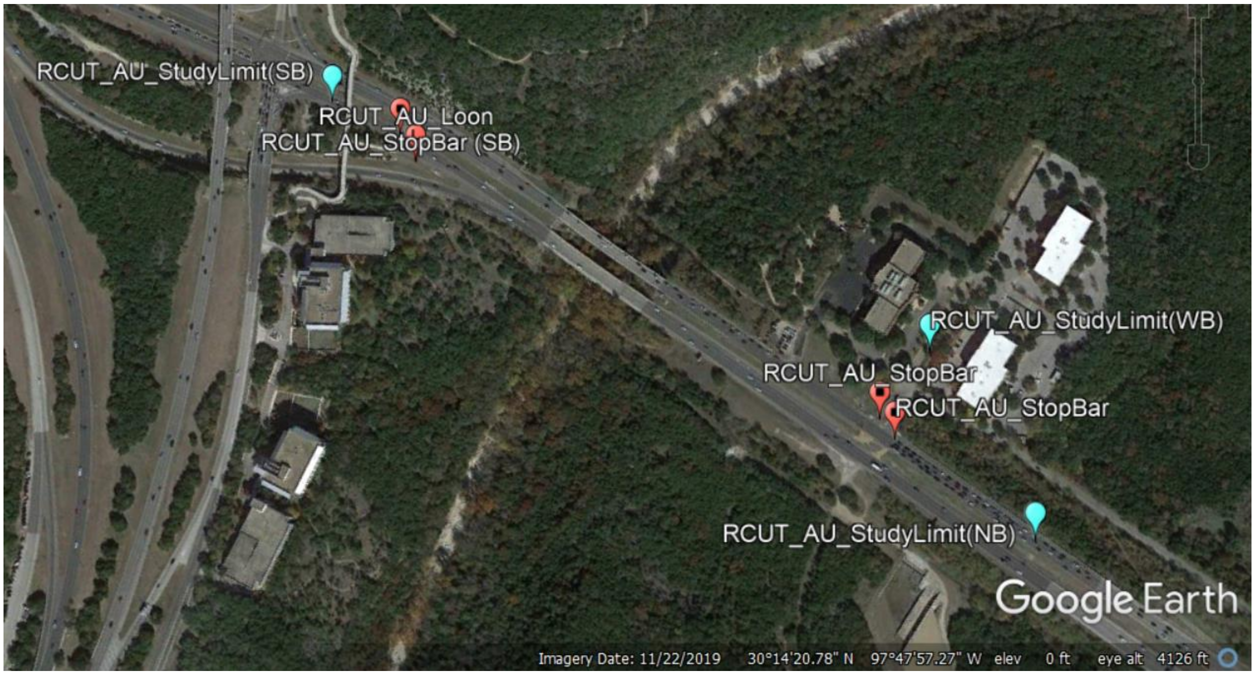



**Figure 86. Determining Limits for RCUT.**

## IDENTIFYING CRASH PATTERNS

### Crash Data Filtering

The research team identified a total of 5,358 CRIS crashes from 2010 to 2019 that occurred within the study limits at selected intersections. The research team then combined the CRIS crash data with the intersection site information; the site information had the following variables: intersection ID, intersection name, latitude and longitude of the intersection, name of main and cross streets, date of installation, PSL, and SSD.

As indicated earlier, identifying the intersection-related crashes in the CRIS database is not trivial and requires a detailed assessment of crash description. This is particularly challenging for the innovative intersections. Therefore, the research team developed a methodology to filter crashes that were not related to the selected intersections. The filtering process was mainly focused on three factors:

- Crash Period: Safety studies suggest using crashes that occurred three years before and three years after the treatment was installed in order to avoid the regression to the mean bias found in crash data (*125*).
- Crashes at Neighboring Intersections: For the initial identification of crashes, the research team set the study boundaries at the estimated limit of the innovative intersection, and then the SSD value was added. In being so generous with the limits, there was the potential to identify crashes associated with a neighboring intersection. These crashes needed to be identified and removed from the analysis.
- Freeway or Mainlane Crashes: Another potential source of incorrectly identifying a crash as being associated with an innovative intersection in Texas is for those designs that are near a freeway. At many DDI and DLTs, the freeway (i.e., main road) does not directly intersect with the cross street but rather an overpass that feeds to the frontage road with the help of exit and entrance ramps. For these intersections, the research team was not concerned with crashes that occurred on the freeway, only those that occurred on the frontage road or ramps on the approaches to the innovative intersections. The freeway crashes needed to be filtered from the database.

**Crash Period**

The research team divided crashes into five groups based on crash period:

1. During Period (i.e., construction): In the absence of other information, the research team assumed that the construction period was six months for MUT and 18 months for DDI, DLT, RBT, and RCUT. The appearance of construction in Google Earth timeline, newspaper articles, and whether the crashes included a flag for construction (Road_Constr_Zone_Fl) was used to refine the construction periods' limits.

2. Before Period: Months before the construction began, capped at 36 months.
3. After Period: Months after the construction ended, capped at 36 months.
4. Prior to Before Period: More than 36 months before construction started.
5. More than 3 yrs After: More than 36 months after construction has ended.

The crashes being considered in the crash analysis would be those that occurred in association with the innovative intersection for up to three years before construction began and three years after construction ended (i.e., Before and After Periods).

**Identifying and Removing Freeway or Mainlane Crashes and Crashes at Neighboring Intersections**

The research team used the following procedure to identify the crashes that needed to be removed from consideration. To accomplish this goal, the research team first assigned crashes to the main and cross streets using the following approach:

1. The street names included in the Rpt_Street_Name and Rpt_Sec_Street_Name variables in the CRIS database can be inconsistent and have missing values. The Highway number data in Rpt_Hwy_Num and Rpt_Sec_Hwy_Num provide information on which street(s) were associated with the crash. These variables were used to identify the streets associated with the crash. The research team created new street name variables so that the updated street names were consistent and matched the names being used with the intersection site information. For example, per the research team's definition, the main and cross street names of DLT_CP intersection were RM 1431/Whitestone Blvd and Reagan/Parmer/FM734, respectively. The CRIS database uses the names "Whitestone" instead of RM 1431, and the names "Parmer," "Parmer Ln," and "Ronald Reagan" instead of Parmer Ln. In these cases, the research team manually compared the street names in the CRIS database and used a common name and spelling selected by the research team in the newly developed fields.
2. Based upon the review of street names provided, the research team assigned each crash to the main street or cross street.
3. While assigning street names, the research team was able to identify if the crash took place at a nearby intersection rather than at the subject intersection. If so, that crash was marked as needing to be dropped from the dataset.

After assigning crashes to main and cross streets, the research team assessed the location where the crash took place on the main and cross street and its relevance to the study site. A crash could take place on the mainlane or along a frontage road or ramp. Moreover, a crash that occurred within the study limits may not be intersection related. The research team implemented the following procedure to identify the crash location on roadway and non-intersection crashes:

1. TxDOT CRIS variable Intrsct_Relat_ID provides a flag when the crash is at an intersection or related to an intersection. Those crashes with an intersection flag of yes were retained, while those with an intersection flag of no were candidates for removal.
2. TxDOT CRIS variable Rpt_Road_Part_ID includes the following codes: mainlane, frontage road, ramps, connector, and other. CRIS includes number values, and these values were converted to the two letter codes to assign crashes to the correct location.

Finally, the research team considered the intersection configuration to decide whether the crash would be kept or dropped. As indicated, at intersections with an overpass, the freeway does not intersect with the cross street. Therefore, the research team manually identified intersections with an overpass and then merged the information on the presence of an overpass, whether the crash occurred on the main or cross street, an intersection-related flag, and which road part was involved to create a new variable. Crashes that took place for sites with an overpass that had an intersection-related flag of no and occurred on the mainlane of the freeway or main road that did not directly intersect with the cross street were dropped from the final dataset.

### Assigning Crashes to Intersection Approaches

After filtering out the non-relevant crashes, the research team assigned each crash to the intersection approach for conducting the exploratory data analysis. The steps used to assign the crash to a given approach were as follows:

1. Calculate the distance (ft) and bearing (radians) between crash and center of the intersection, and assign the crash to one of the four quadrants: northwest (NW), northeast (NE), southwest (SW), and southeast (SE).
2. Compare the quadrant and the street (i.e., main and cross) where the crash took place, and assign the crash to one of the four directions or sides of the intersection: east, west, south, or north. For example, if the crash occurred in the NW quadrant and was on the main

street, then the research team assigned it to the west leg, given that the main street was going from east to west.

## CRASH EXPLORATORY ANALYSIS

### Overview

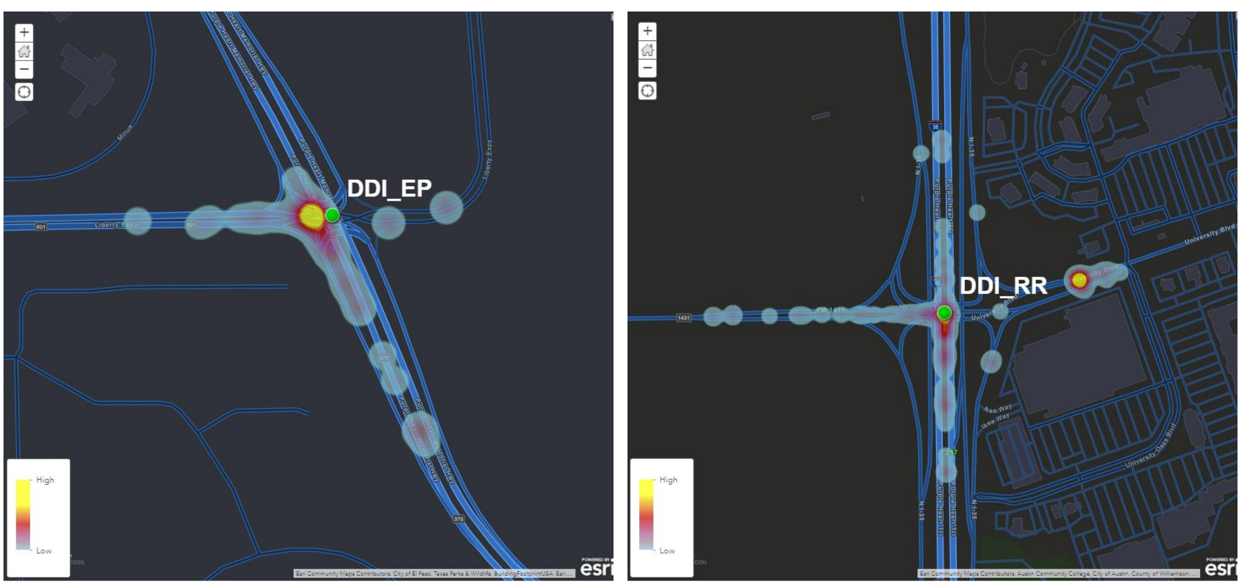
Table 37 provides the number of crashes in the before and after periods for each of the innovative intersections. In several cases, more crashes occurred in the after period as compared to the before period; however, that observation needs to be placed into context. A comparison of the before period to the after period would require the consideration of several factors. For example, the number of months for each period may not be equal since some of the intersections have not been present for the same number of months in the after period as for the before period. When examining crashes, traffic volume is an important variable since crashes are highly related to vehicle volume. It is reasonable to expect traffic volume to be greater in the after period since in addition to typical growth in traffic, the innovative intersection would provide additional capacity that would attract more vehicles and could process more vehicles than the before condition.

With the limited number of sites, this crash analysis focused on comparing the distribution of crashes during the before and after periods to determine trends in crash distributions. In addition, when more than 36 crashes occurred in the after period, the after crashes were plotted on a map to illustrate if there were hot spots within the innovative intersection designs. Figure 87 shows the hot spots for the two DDIs with more than 36 crashes, while Figure 88 shows the crashes within the RCUT. Most of the DLT intersections in Texas have been operating for several years, and the distribution of after crashes are shown in Figure 89.

**Table 37. Number of Crashes and Months in Before, After, and Recent Periods at the Innovative Intersection.**

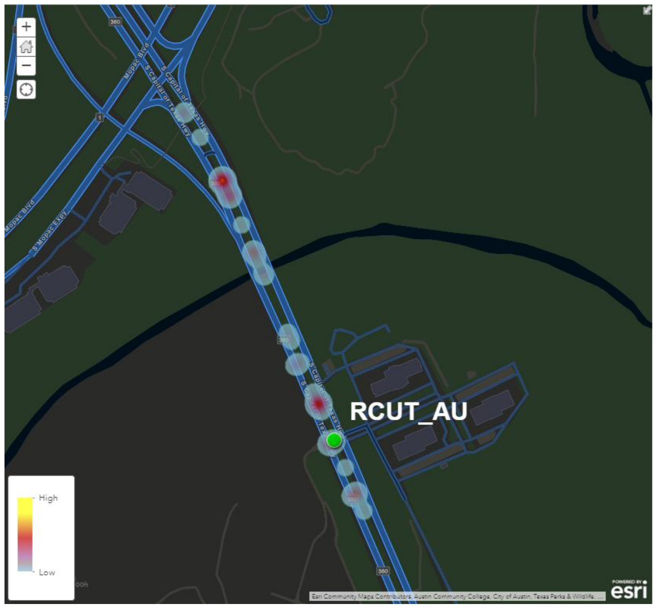
| Intersection | Crashes in Before Period | Months in Before Period | Crashes in After Period | Months in After Period | Crashes in Recent Period[1] | Months in Recent Period |
|---|---|---|---|---|---|---|
| DDI_AU | 18 | 36 | 10 | 11 | NA[2] | NA |
| DDI_CS | 97 | 36 | 9 | 8 | NA | NA |
| DDI_EP | 5 | 36 | 48 | 36 | 30 | 28 |
| DDI_RR | 80 | 36 | 151 | 36 | 50 | 13 |
| DDI_TC[3] | 0 | NA | 2 | 36 | 1 | 10 |
| DLT_AU1 | 75 | 36 | 62 | 36 | 34 | 27 |
| DLT_AU2 | 77 | 36 | 73 | 36 | 65 | 27 |
| DLT_CP | 64 | 36 | 104 | 36 | NA | NA |
| DLT_SA | 539 | 36 | 55 | 6 | NA | NA |
| DLT_SM1 | 117 | 36 | 122 | 36 | 95 | 30 |
| DLT_SM2 | 145 | 36 | 172 | 36 | 103 | 28 |
| MUT_AU | 9 | 36 | 19 | 36 | 44 | 29 |
| MUT_CS | 33 | 36 | 6 | 16 | NA | NA |
| RCUT_AU | 55 | 36 | 59 | 36 | 5 | 12 |
| **Grand Total** | **1315** | **36** | **892** | **Varies** | **429** | **Varies** |

***Note:*** *[1] The After period was capped at 36 months. There were a few intersections where the innovative intersection design had been in place for more than 36 months. This column provides the number of crashes and number of months for that period. The crashes will be used in the review of crash locations on the intersection approaches but not in the comparison of crash distributions.*
*[2] NA = not applicable as the design had been in place for less than 36 months.*
*[3] While the major road existed, the cross street for this innovative intersection did not, resulting in 0 months for the before period.*



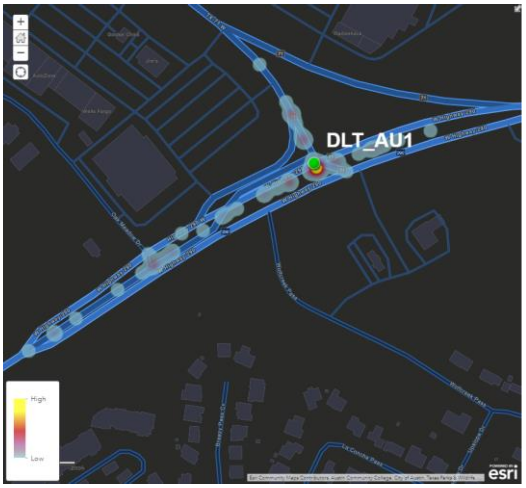

a) DDI El Paso (48 crashes) b) DDI Round Rock (151 crashes)

**Figure 87. Hot Spots within Diverging Diamond Intersections.**



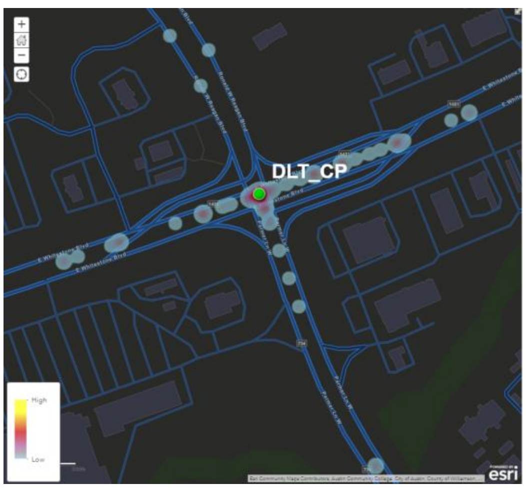

RCUT Austin (59 crashes)
**Figure 88. Hot Spots within Restricted Crossing U-Turn Intersection.**

The crashes that are shown to take place on freeways occurred at frontage roads or ramps, however, based on their coordinates, they were mapped to freeways. Therefore, these images need to be treated carefully since they may not depict the crash's exact location. As observed, overall, most of the crashes took place near the center of the intersection. However certain locations also seem to be prone to more crashes. For example, as observed in Figure 87b, the back of the queue for the east leg has a hot spot. The plots for DLTs (see Figure 89) show several crashes along the approaches to the left-turn lanes, indicating that crashes associated with end of queues could be a concern.

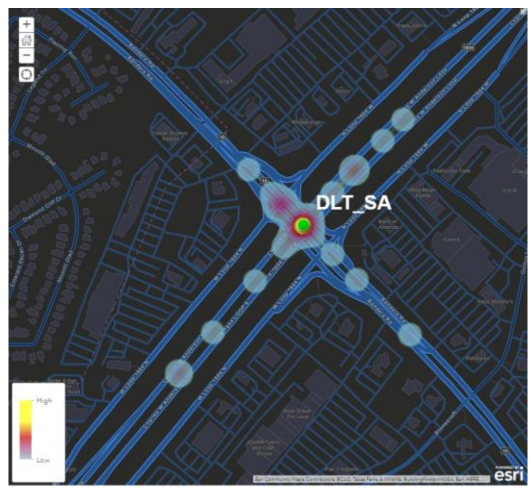



a) DLT Austin #1 (62 crashes)


b) DLT Austin #2 (73 crashes)

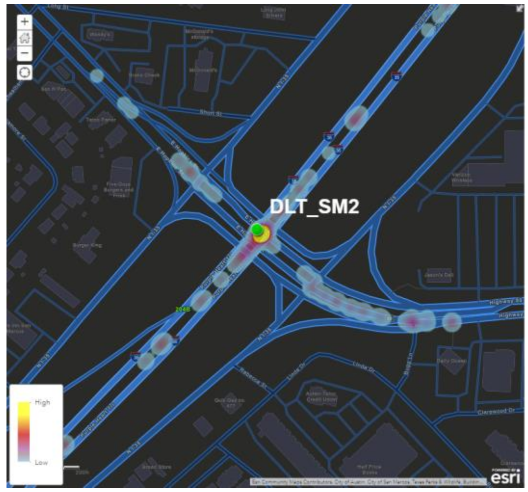



c) DLT Cedar Park (104 crashes)




d) DLT San Antonio (55 crashes)


e) DLT San Marcos #1 (122 crashes)




f) DLT San Marcos, #2 (172 crashes)

**Figure 89. Hot Spots within Displaced Left-Turn Intersections.**

### Crash Severity

Innovative intersection designs separate conflicts, which should result in fewer severe crashes. The KABCO scale is used in Texas where K = fatal, A = suspected serious injury, B = non-incapacitating injury, C = possible injury, and O = no injury or PDO crash. As shown in Table 38, the percent of crashes with no injury (PDO crashes) reflects the greatest percentage for all of the innovative intersection forms. With respect of the before to after period, the proportion of crashes that were no injury crashes (O) increased for all innovative intersection designs except DLTs, which essentially stayed constant. DDIs, MUTs, and RCUTs all showed a greater percentage of O crashes in the after period which means that the proportion of KABC crashes decreased in the after period. For example, in the before period 58 percent of the crashes at DDIs were no injury in the before period. The percentage of no injury crashes increased to 68 percent in the after period, indicating that the proportion of fatal and injury crashes decreased after installing the DDIs. The DLTs showed a similar distribution in the after period compared to the before period for the no injury crashes (e.g., 67 percent before, and 66 percent after).

**Table 38. Severity Distribution per Innovative Intersection Form.**

| Severity | DDI Before | DDI After | DLT Before | DLT After | MUT Before | MUT After | RCUT Before | RCUT After |
|---|---|---|---|---|---|---|---|---|
| A | 3% | 1% | 1% | 1% | 2% | 4% | 0% | 0% |
| B | 16% | 15% | 11% | 14% | 21% | 8% | 15% | 0% |
| C | 22% | 15% | 20% | 18% | 7% | 12% | 20% | 14% |
| K | 1% | 1% | 0% | 0% | 2% | 0% | 0% | 0% |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| O | 58% | 68% | 67% | 66% | 67% | 76% | 65% | 86% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

**Collision Type**

CRIS has several variables that can provide insights into the collision type and other factors associated with the crash. The research team used the collision variable and defined a new variable to better focus on the questions of whether there were changes in the distribution for movement (e.g., right versus left-turn crashes) and crash type (e.g., single vehicle, angle, etc.).

The collision variable in CRIS provides information on the number of vehicles (one or more than one), the direction of the vehicle(s), and the crash type. According to this project's needs, the research team reorganized the data to focus on crash movement (see Table 39) and crash type (see Table 40). A key aspect for innovative intersection designs is to manage the left-turn conflicts. As illustrated in Table 39, each of the four innovative intersection forms saw a reduction in the percent of left-turn crashes in the after period. For the DDIs, the percent of the crashes associated with a left-turning vehicle went from 31 percent in the before period down to only 4 percent in the after period. DLTs went from 29 percent down to 19 percent.

**Table 39. Crash Movement Distribution per Innovative Intersection Form.**

| Movement | DDI Before | DDI After | DLT Before | DLT After | MUT Before | MUT After | RCUT Before | RCUT After |
|---|---|---|---|---|---|---|---|---|
| Left Turn (LR) | 31% | 4% | 29% | 19% | 12% | 4% | 2% | 0% |
| Left/Right (LT-RT) | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Right Turn (RT) | 3% | 2% | 8% | 9% | 2% | 12% | 2% | 0% |
| Straight | 66% | 94% | 63% | 72% | 86% | 84% | 96% | 100% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

The percent of head-on crashes in the after period was less for both the DDIs and the DLTs. DDIs had fewer angle crashes but more sideswipe crashes, while the DLTs had fewer sideswipe crashes and more angle crashes. The MUTs experienced a greater proportion of head-on and angle crashes in the after period and fewer single-vehicle crashes.

**Table 40. Crash Type Distribution per Innovative Intersection Form.**

| Crash Type | DDI Before | DDI After | DLT Before | DLT After | MUT Before | MUT After | RCUT Before | RCUT After |
|---|---|---|---|---|---|---|---|---|
| Angle | 15% | 5% | 15% | 20% | 7% | 16% | 4% | 0% |
| Head-on | 27% | 2% | 16% | 14% | 0% | 4% | 2% | 0% |
| Other | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Rear-end | 12% | 19% | 10% | 12% | 7% | 8% | 31% | 34% |
| Sideswipe | 34% | 55% | 52% | 43% | 21% | 20% | 51% | 51% |
| Single Vehicle | 11% | 20% | 7% | 11% | 64% | 52% | 13% | 15% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

**Other Factors**

CRIS includes an "other factor" variable to indicate the pre-crash maneuver, which has over 50 values. Table 41 summarizes the distribution of other factors for both the before and after periods by innovative intersection form. Some of the factors that were similar and that had small percentages were combined for space reasons. For example, the seven swerved or veered factors were combined into two rows in Table 41, one related to swerving or veering due to another vehicle and the other related to all remaining cases such as animals or an object on the road.

The DDIs had several shifts between the before and after periods, with the factor of not applicable used less often while the (a) vehicle changing lanes and (b) slowing or stopping for traffic control factors were used much more frequently. The DLTs had a similar distribution for the other factor variable in both the before and after periods. The largest shift for MUTs was the lost control factor that was observed less frequently in the after period compared to the before period—a factor that is probably not related to the intersection design. The RCUTs had several shifts from before to after. The pre-crash maneuvers observed more frequently in the after period included the following: attention diverted from driving, slowing/stopping for traffic, and construction not related to crash. Those factors that were observed less frequently in the after period included: slowing/stopping reason not specified, slowing/stopping for traffic control, and not applicable.

**Table 41. Other Factors Distribution per Innovative Intersection Form**

| Other Factors | DDI Before | DDI After | DLT Before | DLT After | MUT Before | MUT After | RCUT Before | RCUT After |
|---|---|---|---|---|---|---|---|---|
| Lost control or skidded (icy or slick road, etc.) | 1.5% | 2.3% | 1.1% | 0.9% | **33.3%** | **16.0%** | 5.5% | 1.7% |
| Attention diverted from driving | 8.0% | 10.9% | 12.5% | 13.3% | 2.4% | 0.0% | **1.8%** | **8.5%** |
| Vehicle changing lanes | **6.0%** | **17.3%** | 4.8% | 6.8% | 4.8% | 8.0% | 3.6% | 3.4% |
| One vehicle, driveway related | 2.0% | 0.5% | 10.7% | 8.3% | 2.4% | 4.0% | 3.6% | 0.0% |
| Vision obstructed | 1.0% | 0.0% | 0.0% | 0.7% | 0.0% | 0.0% | 0.0% | 0.0% |
| Swerved or veered, animal, object, etc. | 0.5% | 0.5% | 0.0% | 0.3% | 4.8% | 4.0% | 0.0% | 0.0% |
| Swerved or veered, vehicle related | 2.5% | 4.1% | 1.5% | 1.7% | 0.0% | 4.0% | 1.8% | 5.1% |
| Slowing/stopping, reason not specified | 1.0% | 2.7% | 1.4% | 1.7% | 0.0% | 0.0% | **9.1%** | **3.4%** |
| Slowing/stopping, traffic control, etc. | **8.5%** | **16.4%** | 14.9% | 16.8% | 4.8% | 8.0% | **23.6%** | **16.9%** |
| Slowing/stopping, for traffic | 18.4% | 15.0% | 16.7% | 11.7% | 7.1% | 4.0% | **23.6%** | **32.2%** |
| Slowing/stopping-to make right turn | 0.0% | 0.0% | 1.8% | 1.5% | 0.0% | 0.0% | 0.0% | 1.7% |
| Slowing/stopping-to make left turn | 3.0% | 0.0% | 1.3% | 1.2% | 0.0% | 0.0% | 0.0% | 0.0% |
| Construction—not related to crash | 2.5% | 6.4% | 4.5% | 6.0% | 2.4% | 0.0% | **1.8%** | **8.5%** |
| Construction—related to crash | 1.0% | 1.4% | 0.0% | 0.2% | 2.4% | 4.0% | 0.0% | 0.0% |
| Other | 0.0% | 0.9% | 0.6% | 1.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Not applicable | **44.3%** | **21.8%** | 28.2% | 27.9% | **35.7%** | **48.0%** | **25.5%** | **18.6%** |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

*Note: Grey highlighted bold cells represent more than a five-point shift (either positive or negative) from the before to the after period.*

# CHAPTER 7: FINDINGS AND CONCLUSIONS

This chapter summarizes the work completed throughout the project, as documented in the previous chapters of this report, and provides a listing of the researchers' key conclusions. This chapter also includes the researchers' recommendations for future action based on those conclusions.

## SUMMARY OF PROJECT ACTIVITIES

The project was organized into two distinct sets of tasks conducted simultaneously; one set of tasks was specific to roundabouts and the other set of tasks to innovative intersections. The separate tasks allowed the research team to focus necessary attention on the unique characteristics of each intersection category, while the single project provided a means to combine activities and share findings jointly when it was most efficient.

### Roundabouts

A review of existing guidance and relevant research on roundabouts with high-speed approaches provided a basis for the current state of the practice. Researchers obtained information on high-speed and/or rural roundabouts in 14 states during the Task 2 review; many of those states have state-specific design guidance, while others generally use NCHRP Report 672 in whole or in part. A summary of relevant research and guidance indicated the following key findings:

- Key features found at roundabouts include:
    - Balance between lower circulating speeds and higher approach speeds.
    - Selection of appropriate design vehicle(s).
    - Speed reduction elements on approaches (curves, extended splitter island with curb).
    - Larger central island, truck apron, and wider lanes compared to urban/low-speed roundabouts.
    - Supplemental traffic control devices and lighting in advance of and at the intersection.

- Research supports:
    - Using specific design elements on high-speed approaches to roundabouts and in the intersections to encourage speed reduction.
    - Using traffic control devices to supplement the design and provide advance notice to approaching drivers.
    - Using roundabouts to provide improvements in crash reduction and injury reduction over the intersection designs they replace.

The field data collection effort included identifying potential study sites for roundabouts with high-speed approaches, rural locations, and/or heavy vehicle volumes; selecting appropriate sites for data collection; developing and executing a field data collection plan; and reducing the field data. Data were collected at three locations, two in Kansas and one in Texas, with in-state data collected through traditional methods (i.e., ground-based video recording, lidar speed guns, and traffic classifiers) and out-of-state data collected by unmanned aerial vehicle (i.e., drone). The data collected through the drone-based video footage were reduced and used to develop microsimulation models to evaluate operational performance of roundabouts with varying inscribed circle diameters as well as two-way stop-controlled intersections with multiple levels of traffic volumes, heavy vehicle percentages, and OSOW vehicle percentages.

**Innovative Intersections**

This report documents site data collection efforts for the following two study sites:

- NC-IT: US-74 and Sardis Church Road.
- NC-MOT: US-74 and Faith Church Road.

The data collection for each of the sites was conducted individually using different methods. At the NC-IT: US-74 and Sardis Church Road site the research team used a set of five drones that covered the study segment from a perpendicular view. At the NC-MO: US-74 and Faith Church Road site, two drone-mounted cameras were tilted such that each could cover one side of the intersection.

The findings from the simulation show that a spacing of a minimum of 700 ft between the main intersection and the downstream U-turn intersection resulted in higher operating speeds compared to a conventional signalized intersection. A spacing of 1,500 ft or more generated higher operating speeds for both the major and minor road drivers. As expected, operating speeds decreased as minor road, major road, or truck percentages increased.

The material in this report presents the results of the exploratory crash analysis for innovative intersections installed in Texas. The research team first identified the list of existing innovative intersections installed in Texas and then the date of installation to determine whether the site could be used in a before-and-after analysis.

To select the relevant crashes, the research team started with identifying the innovative intersection boundaries and then the study site limits based on stopping site distance. The research team then spent time to refine the boundaries and limits of the study sites to accurately capture the crashes related to the innovative intersection rather than to a neighboring intersection or the nearby freeway. The research team developed a protocol for assigning crashes to (a) main and cross streets, (b) a location on main and cross street, and (c) intersection approaches. During this effort, the goal was to confirm that the crash selected for the exploratory analysis was indeed related to the innovative intersection.

After selecting the relevant crashes, the research team developed figures to indicate hot spots within the innovative intersection design. The visual analysis indicated that most of the crashes occurred at the center of the intersection, although these figures need to be treated carefully since it appears that several of the crashes did not occur at the exact coordinates provided. Researchers then conducted a before-and-after comparison of crash severities, crash types and movements, and other crash-contributing factors. The factors that contributed to crashes at innovative intersections more in the after period were vehicle changing lanes, attention diverted from driving, and slowing/stopping for traffic. The key findings of this analysis were that each of the four innovative intersection forms saw a reduction in the percent of left-turn crashes in the after period. Moreover, the severity of the crashes reduced considerably after the installation of the innovative intersections; a higher percentage of crashes occurring in the after period were non-injury crashes.

## SUMMARY OF KEY FINDINGS

Results from microsimulation indicate that a roundabout can accommodate large daily volumes, as well as heavy vehicle and OSOW percentages, at a level of service that exceeds traditional two-way stop control. While all the simulated roundabouts were able to accommodate the heavy vehicles, as the inscribed circle diameter increased, so did the operational performance. The findings from the field studies and analyses of roundabout data indicate the following:

- Roundabouts in rural locations and/or with high-speed approaches are rare in Texas, particularly those with substantial truck volumes; however, such roundabouts are being built in other states and have existed for over a decade.
- Traditional data collection and reduction methods (i.e., ground-based video, lidar, traffic classifiers, manual review) are generally inefficient and exceed their limitations for larger roundabouts, particularly those with multiple lanes and/or large numbers of heavy vehicles. Technological improvements in drone capabilities and algorithm-based automated reduction software have made those data collection and reduction methods much more suitable and efficient for obtaining the necessary data at roundabouts.
- Roundabouts can be designed to accommodate not only heavy vehicles but also OSOW vehicles in rural locations with high-speed approaches. The roundabout with the largest diameter (180 ft) had the best performance, but the smallest roundabout (120-ft diameter) was also able to accommodate the larger vehicles at lower volumes.
- The traditional two-way stop-control alternative was not able to process the simulated volumes, trucks, and OSOW vehicles as efficiently as the roundabouts and produced a LOS F for volumes of 10,000 ADT and higher. Delay per vehicle was similar for TWSC and roundabouts at 5,000 vehicles per day, but at 10,000 vehicles per day, the difference in delay was pronounced, with roundabout delays no more than 50 seconds/vehicle and TWSC delays generally over 150 seconds/vehicle.
- Larger roundabouts were able to process 10,000 vehicles per day with varying truck and OSOW percentages, even at 10 percent OSOW, which far exceeds the OSOW volume that an intersection would normally experience in a typical day.
- Larger roundabouts were also able to accommodate up to 15,000 vehicles per day with no more than 20 percent trucks or 5 percent OSOW vehicles before reaching LOS F.

The findings from the field studies and analyses of innovative intersection data indicate the following:

- The use of innovative intersections is growing within the country and within Texas. Research indicates that these intersection forms can result in fewer crashes. A 2017 study for RCUTs (*112*) recommended a CMF of 0.78 for injury crashes, while a 2020 study (*114*) suggested a CMF of 0.5726.
- A study on J-turns found the spacing of 1,500 ft or greater experienced the lowest crash rates, and while spacing between 1,000 and 2,000 ft was found to be sufficient for low-volume combinations, a spacing of 2,000 ft between the main intersection and the U-turn was recommended for medium- to high-volume conditions.
- The simulation analysis conducted within this project considered a range of spacings between the main intersection and the U-turn intersection. Spacings less than 1,000 ft resulted in notably lower performance. Overall, the 2,000-ft spacing had the highest average speed for the overall corridor and for the vehicles turning left from the major road and from the minor road.
- The safety review of existing Texas innovative intersections considered DDIs, DLTs, MUTs, and a RCUT. The key findings of this analysis were that each of the four innovative intersection forms saw a reduction in the percent of left-turn crashes in the after period. Moreover, the severity of the crashes reduced considerably after the installation of the innovative intersections; a higher percentage of crashes occurring in the after period were non-injury crashes.

## SUMMARY OF RESEARCH NEEDS

Based on the reviews conducted in Tasks 2 and 3 of this project, the following topics have been identified as needing additional research to help fill information gaps and provide needed insights. The research team has grouped the topic ideas into three broad categories of technical topics (top, middle, lower) and one category on communication.

## Research Topics Grouped into Top Category

- **Accommodation of heavy vehicles, crossover-based intersections.** Offtracking associated with larger vehicles is well documented on curves. However, research and techniques to accommodate offtracking at crossover-based intersections is lacking. These intersections are unique in the sense that motorists experience several alignment changes as they traverse the intersection, even if they are just proceeding straight through. To assist practitioners in designing these types of facilities, a synthesis of techniques applied at other facilities (e.g., truck aprons) and their applicability to the crossover-based design is needed.
- **Relationship between approach design and operating speed for roundabouts.** The most important design objective for roundabouts is to maintain low and consistent speeds throughout the roundabout. The operating speed of a roundabout is widely recognized as one of its most important attributes in terms of safety performance. While the roundabout itself is designed with low speeds in mind, it is also necessary for the approaches to the roundabout to encourage a transition from the prevailing speed upstream to the lower speed in the intersection. A variety of speed-reduction treatments have been studied, both design treatments and traffic control device treatments, but reported results have been mixed. An examination of operating speeds based on the design features and traffic control devices present on the approaches could help provide additional insight into what treatments are effective for encouraging necessary speed reduction on roundabout approaches.

## Research Topics Grouped into Middle Category

- **Examples of schematics and best practices for signing and marking at alternative intersections.** As more TxDOT districts consider implementing alternative intersections, the lack of specific guidance regarding signing and marking at these types of intersections can result in variations across the state. This research effort would include identifying practices in other states along with reviewing the practices already used within the state to develop typical schematics showing appropriate signing and marking for a specific alternative intersection type. Unique efforts will be needed based on the type of alternative intersection as U-turn-based intersections (e.g., RCUTs) have different guidance and regulatory signing and markings needs as compared to crossover type intersections (e.g., DDIs).

- **Appropriate pedestrian crossing treatments for roundabout approaches.** The lower speed environments at roundabouts contribute to improved operations and safety for pedestrians and bicyclists, as does a splitter island design that facilitates pedestrians crossing one direction of vehicle traffic at a time with pedestrian refuge between. In some cases, however, traffic control is needed for visually impaired pedestrians to cross. NCHRP 674 (*Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*) (*126*) provides insights and suggestions on treatments for those situations. As newer pedestrian crossing traffic control devices are being used, such as the rectangular rapid flashing beacon (RRFB) or the pedestrian/school crossing sign with embedded LEDs, additional research is needed to determine if they are appropriate for roundabouts, as well as selected portions of alternative intersections.
- **Pedestrian and bicyclist paths within an alternative intersection.** Pedestrians approach alternative intersections on a sidewalk or walkway adjacent to vehicular traffic and then engage in the task of identifying the intended route or path through the alternative intersection. The pedestrian may take the intended route or may not find it or decide another route is shorter or more convenient. This research is to compare the route pedestrians are actually taking within an alternative intersection design to the facilities provided. Similar path identification and decisions occur for bicyclists. Are pedestrians and bicyclists using these intersections as intended? With the growing use of other personal devices commonly called micro-mobility, research could consider how these users would navigate these intersections.
- **Accommodation of heavy vehicles, U-turn-based intersections.** While guidance regarding U-turn intersection design exists (e.g., including a loon to accommodate the larger turning path of a heavy vehicle), an under-evaluated

consideration of heavy vehicle traffic in U-turn-based intersections is accommodation of the weaving and lane-changing that may be necessary for a heavy vehicle to turn right from the side street to the main street and then navigate across traffic to use the U-turn intersection. The issue is likely to be more pronounced at locations with multiple right-turn lanes or where U-turn intersections are applied both as an intersection treatment and to facilitate circulation along the entirety of the corridor. To optimize these designs for heavy vehicles, information highlighting challenging designs for heavy vehicles is needed.

- **Separation distance to adequately accommodate queuing, crossover-based intersections.** Similar to U-turn-based intersections, crossover-based intersections are actually several smaller intersections functioning together. The proximity of the DCIs (in the case of the DDI) or the crossover intersections to the main intersection (in the case of DLTs) plays a significant role in the operation of the traffic facility. Existing guidance suggests that traffic microsimulation be used to identify the proper distances between these intersection elements; however, planning-level guidance could assist road agencies in determining the feasibility of the alternatives earlier in the planning process.

**Research Topics Grouped into Low Category**

- **Examples of schematics for signing and marking at roundabouts**. There is a great deal of existing guidance on signing and marking for roundabouts, much of which can be found in the federal MUTCD, the Texas MUTCD, and NCHRP Report 672. Previous state-of-the-practice reviews and other presentations available within the profession also provide many examples of that guidance being implemented at real-world sites as best practices, as well as some examples of other practices that are not recommended and why. One example within the profession was whether (and how) to stripe multilane roundabouts because of the likelihood of driver confusion, increased sideswipes, and other operational issues associated with no striping on a wide circulating roadway. The MUTCD now contains recommended striping examples. Further documentation of best practices and the support for them will provide practitioners ready examples of appropriate signing and marking for future roundabouts.

- **Access limitations for each alternative intersection form.** Research could identify the appropriate access restrictions or limits by alternative intersection form. For example, it should be safer and more efficient to limit access along the right-turn lanes/ramps of a DDI.
- **Crossover intersection angle**, **crossover-based intersections.** Guidance for DDIs indicates that the crossover intersection angle should be as close to 90 degrees as possible to simulate a typical intersection and thus reduce the likelihood of wrong-way driving. Some guidance for DLTs recommends crossover intersection angles between 10 and 15 degrees dependent on median width and mainline alignment, while other guidance is more broadly stated as the design should help reduce the possibility of wrong-way entry as much as possible. However, constructed sites have a variety of intersection angles. To provide clarity on this issue, wrong-way vehicle rates at a variety of intersecting angles should be examined in conjunction with operational characteristics to further identify a range of desirable values.

**Research Topics Grouped into Communications Category**

- **How to best promote these treatments in Texas**. Because many of these intersection types and their design elements are not commonly used in Texas, there is a natural tendency to be cautious about their use. Providing information to help promote these treatments for use in appropriate locations will be important to their successful adoption and implementation. Review of experiences within Texas and elsewhere suggests three categories or phases of developing a successful promotion:
    - **Examples describing improvements from an engineering perspective**. The road agency making the decision on what type of intersection to use needs to have information to support the operational and safety benefits of that intersection type in order to have any basis for considering it as a potential

option. Roundabouts have a proven track record of reducing the number and severity of crashes and reducing speeds when appropriately designed. Innovative intersections are designed to reduce delay and potential conflicts (especially with left-turn movements) compared to conventional intersection designs. Putting detailed information of this nature into the hands of the planners and designers who initially decide which alternatives to consider increases the likelihood that they will be able to select the intersection type that best meets the needs of the location in question. An investigation of the best methods for sharing that information with initial decision-makers will be beneficial. While the group of initial decision-makers includes planners and designers, specific projects often have others who provide input, such as managers, department heads, or district engineers; those individuals should be included in the group to receive this information from the outset of the project.

- **Finding champions within TxDOT and local politicians.** After an engineering analysis has determined that a particular intersection type is a worthwhile alternative to pursue, someone within the road agency needs to be in a position to promote it for acceptance. Within TxDOT, that person should be at the district or area level to provide the connection to local conditions and the involvement with the details of that particular project. As part of this process, it may also be necessary to include local elected officials in the discussion to obtain their approval for consideration. Experience indicates that having a champion in the road agency who is willing and able to lead that effort greatly improves the chances of implementing a particular intersection type.
- **Example of successful implementations**. After the applicable authorities have indicated their willingness to proceed with a given intersection type as a preferred alternative, it is often necessary (or at least beneficial) to demonstrate to the general public how the chosen design will provide benefit to the location in question, particularly if it is the first installation of that intersection type in the area. This can be achieved through sharing examples of successful implementations of that intersection type in other locations and

how similar benefits can be expected with the proposed installation. In many cases, it may be necessary to use out-of-state examples for early implementations, which can affect how that information is shared. Perhaps using the current model for public information meetings as a template would be beneficial to describe a process for obtaining the necessary information on successful implementation, assembling that information in a format to share with the general public, and understanding the characteristics of the potential audience to maximize the effectiveness of that information so that the public has access to the relevant information they need to understand the design that is being proposed.

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# APPENDIX A: VALUE OF RESEARCH ASSESSMENT

The research team completed a Value of Research (VoR) assessment as part of the project. The VoR assessment was based on the benefit areas selected at the beginning of the project (shown in Table 42).

**Table 42. Selected Benefit Areas for VoR Assessment.**

| Selected | Benefit Area | Qualitative | Economic | Both | TxDOT | State | Both | Definition in context to the Project Statement |
|---|---|---|---|---|---|---|---|---|
| X | Traffic and Congestion Reduction | | X | | | X | | Improved capacity and reduced delay for traffic on rural intersections. |
| X | Engineering Design Improvement | | | X | | | X | Provision for roundabouts and RCUTs on rural and high-speed highways. |
| X | Safety | | | X | | | X | Reduction in crashes and associated injuries and fatalities associated with the improved intersections. |

The VoR assessment is based on the assumption that one existing intersection will be converted to a roundabout annually based on this research project. Additional assumptions are as follows:

- Entering volume of intersection = 6000 vehicles per day.
- Percent heavy vehicles in intersection = 10 percent.
- Previous intersection control = 2-way stop.

The assumptions above represent values that are in the lower to middle part of the range of values studied in the research. Increasing any of the values of those assumptions would add further benefit to the VoR calculations. The Life Cycle Cost Estimation Tool developed for NCHRP Web-Only Document 220 calculated the monetary values of the necessary variables, which are as follows:

- Variable 1: Time cost savings.
- Variable 2: Safety benefits.
- Variable 3: Capital costs.

Table 43 shows the assignment of those variables to the appropriate economic benefit area for the VoR assessment.

**Table 43. Value of Variables for VoR Assessment.**

| Economic Benefit Area | Variable 1 | Variable 2 | Variable 3 | Variable 4 | Variable 5 | Total |
|---|---|---|---|---|---|---|
| Traffic and Congestion Reduction | $744,970.93 | | | | | $744,970.93 |
| Engineering Design Improvement | | | -$2,000,000.00 | | | -$2,000,000.00 |
| Safety | | $40,295,340.79 | | | | $40,295,340.79 |

The research team entered the values shown in Table 43 into the TxDOT VoR Assessment spreadsheet to calculate the formal VoR measures. Those results are shown in Table 44. The results show that, based on the assumptions provided previously, the research project is estimated to have a benefit-cost ratio of approximately 648:1 over a 10-year expected value duration, with over $350 million in savings.

**Table 44. Results of VoR Assessment for Project 0-7036.**

| | | | | |
|---|---|---|---|---|
| Texas Department of Transportation | **Project #** | 0-7036 | | |
| | **Project Name:** | Use of Roundabouts and Innovative Intersection Designs at High-Speed Intersections in Texas | | |
| | **Agency:** | TTI | **Project Budget** | $ 499,968 |
| | **Project Duration (Yrs)** | 3.0 | **Exp. Value (per Yr)** | $ 39,040,312 |
| **Expected Value Duration (Yrs)** | | 10 | **Discount Rate** | 3% |
| **Economic Value** | | | | |
| **Total Savings:** | $ 350,862,837 | | **Net Present Value (NPV):** | $ 323,940,686 |
| **Payback Period (Yrs):** | 0.012806 | | **Cost Benefit Ratio (CBR, $1 : $___):** | $ 648 |

# APPENDIX B : PRELIMINARY FINDINGS ON DESIGN GUIDELINES FOR ROUNDABOUTS AND ALTERNATIVE INTERSECTIONS

## OVERVIEW OF GUIDELINES

The use of roundabouts and innovative intersection designs is increasingly common in Texas, which increases the need for guidance on how to select the appropriate intersection form and its corresponding design features. These guidelines provide information on:

- The characteristics of various intersection forms and types.
- Discussion on how to select an appropriate intersection type for a particular location.
- Design guidance for roundabouts and innovative intersections.
- Access management considerations to include in the planning and design process.
- Guidance on traffic control devices for each intersection type.
- References that provide more detailed information and support for the guidelines in this document.

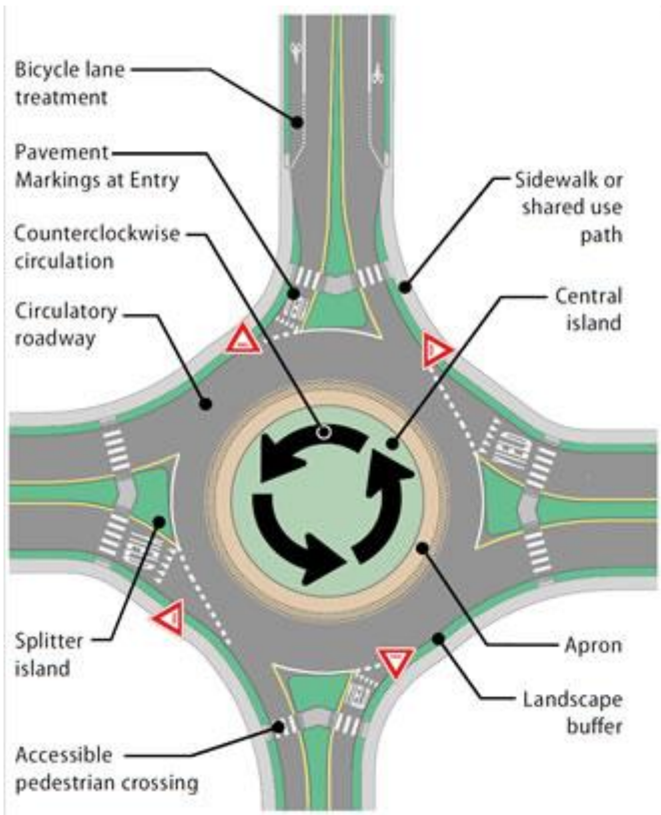
## INTERSECTION FORMS/INTERSECTION TYPES

As traffic demands increase and context-sensitivities expand, conventional intersection designs, whether signalized or unsignalized, are not satisfying local criteria or the transportation network needs. The Texas Department of Transportation (TxDOT) previously funded the development of a guide to assist in conventional intersection design (see *Urban Intersection Design Guide* [*1*] developed as part of Research Project 0-4365). With the growing interest in alternatives to conventional intersection designs, a new document is needed to cover these new intersection forms. This document covers two broad categories of intersection forms: roundabouts and innovative intersections.

The Federal Highway Administration (FHWA) uses three broad categories to classify innovative intersections (also known as alternative intersections or unconventional intersections): U-turn-based, crossover-based, and other. U-turn-based intersections are used on median-divided roadways and function by restricting left-turn and through movements at the main intersection and providing U-turn intersections (sometimes referred to as crossovers) through the median downstream of the main intersection.

**Roundabouts**

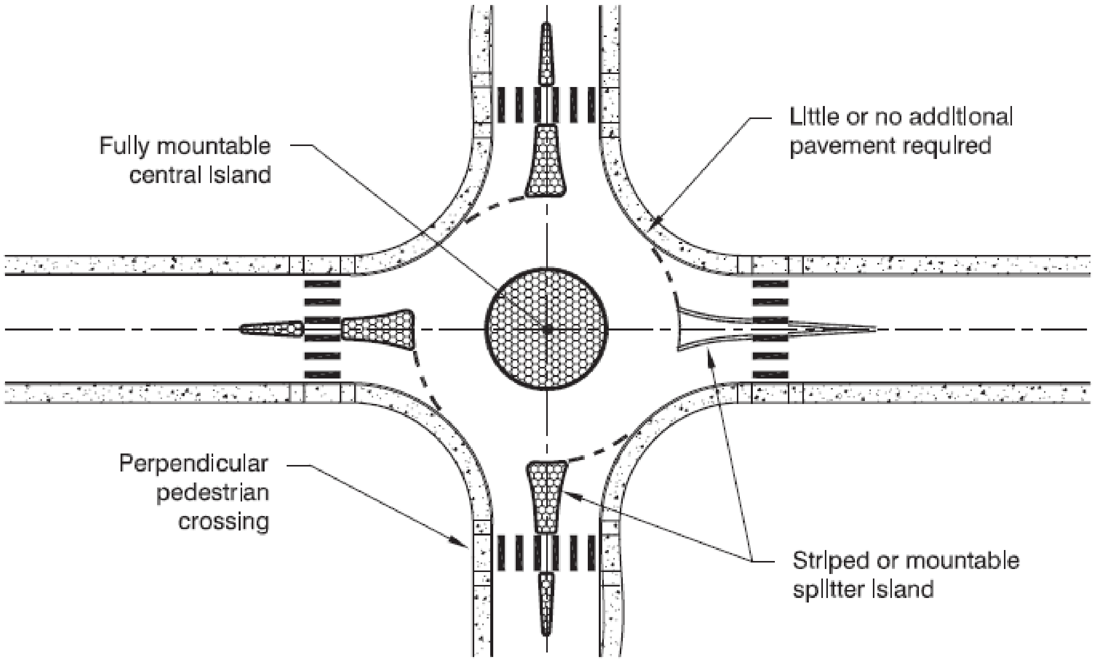
Roundabouts are generally circular intersections where the radius and angle of entry are designed to slow traffic speeds (see Figure 90). Vehicles approaching the roundabout must yield to circulating traffic before entering; vehicles travel counter-clockwise through the circulating roadway before exiting at the desired exit leg. Splitter islands on each leg separate entering and exiting traffic, deflect and slow entering traffic, and provide a pedestrian refuge. Roundabouts can have one lane or multiple lanes.




Source: FHWA Office of Safety Roundabouts Resource Page.
https://safety.fhwa.dot.gov/intersection/innovative/roundabouts/

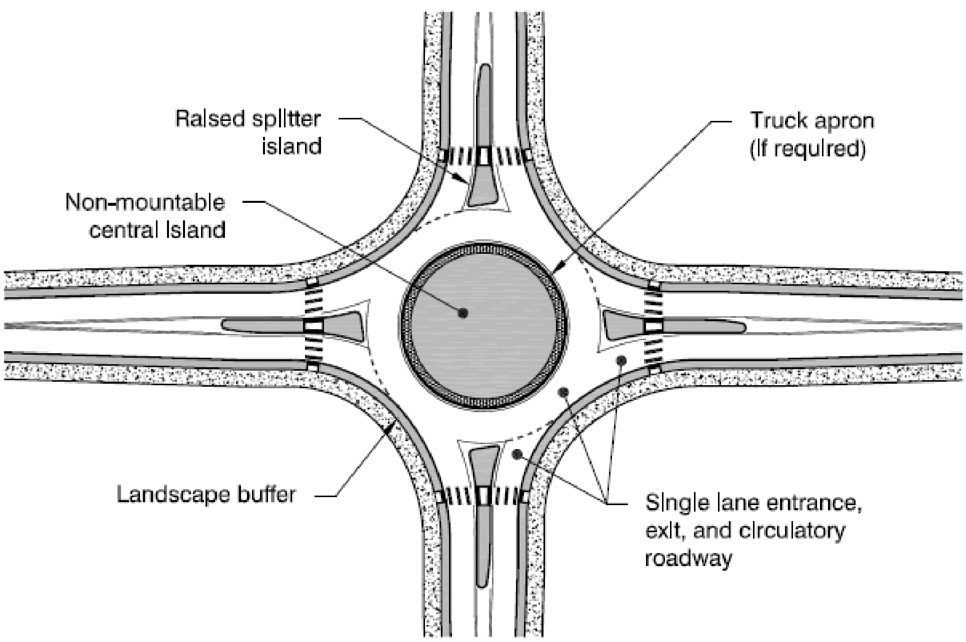
**Figure 90. Example of Roundabout Intersection.**

Roundabouts can be separated into three basic categories according to size and number of lanes to facilitate discussion of specific performance or design issues: mini-roundabouts (see Figure 91), single-lane roundabouts (see Figure 92), and multilane roundabouts (see Figure 93 and Figure 94). Note that separate categories are not explicitly defined for rural, urban, and suburban areas.



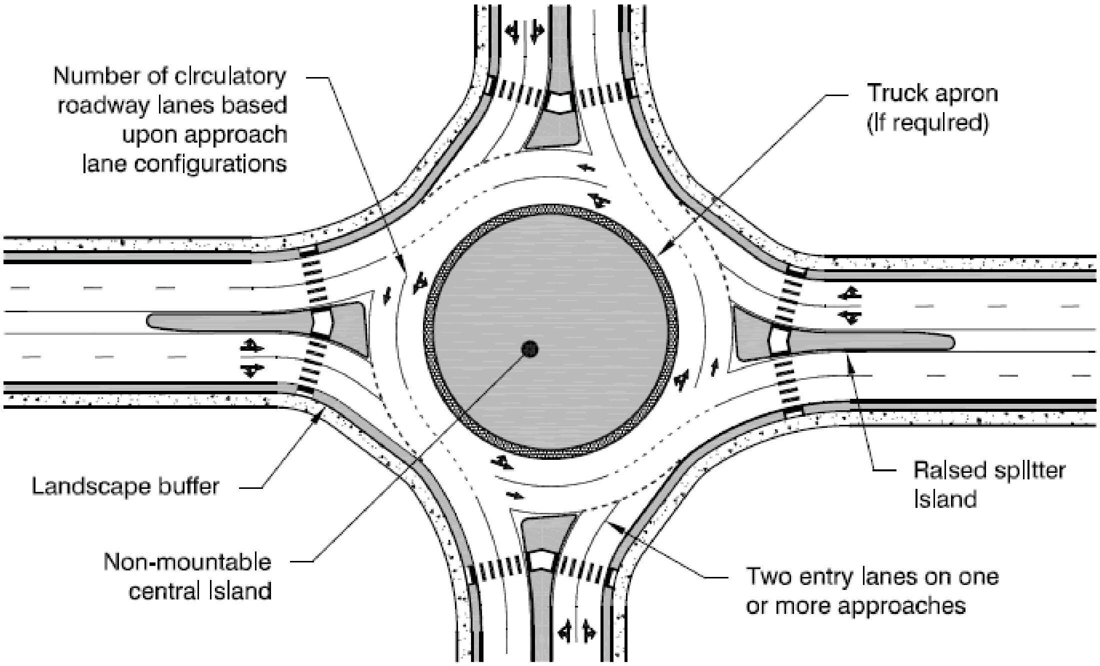

Source: National Cooperative Highway Research Program (NCHRP) Report 672, Exhibit 1-10, Page 1-12.

**Figure 91. Features of Typical Mini-Roundabout (*2*).**



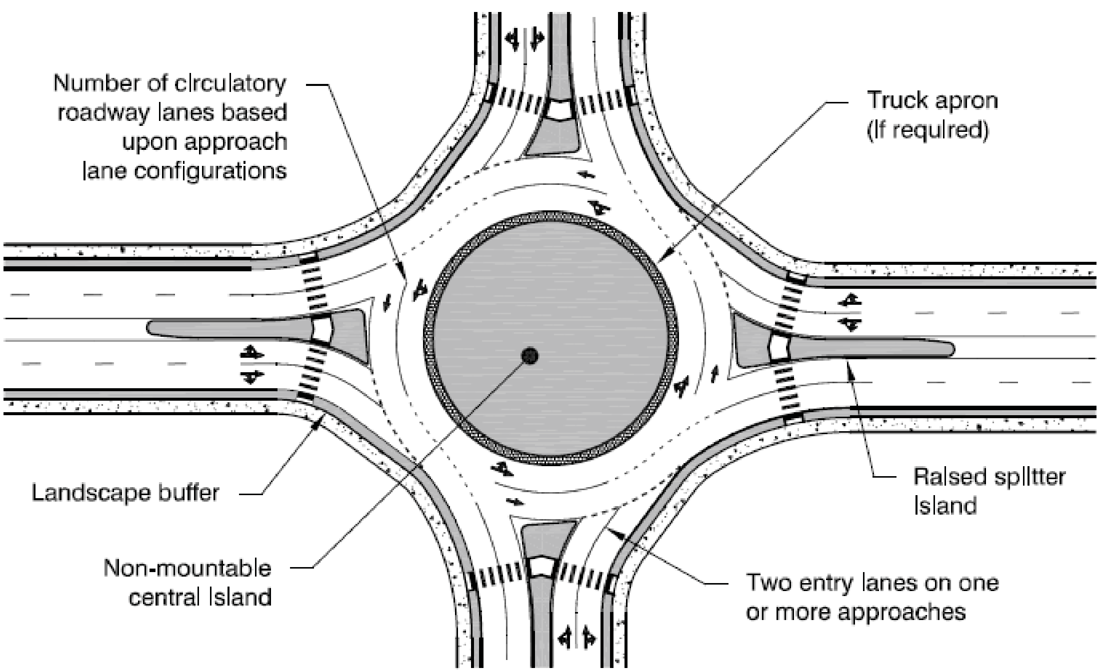

Source: NCHRP Report 672, Exhibit 1-12, Page 1-14.

**Figure 92. Features of Typical Single-Lane Roundabout (*2*).**




Source: NCHRP Report 672, Exhibit 1-14, Page 1-15.

**Figure 93. Features of Typical Two-Lane Roundabout (*2*).**




Source: NCHRP Report 672, Exhibit 1-15, Page 1-15.

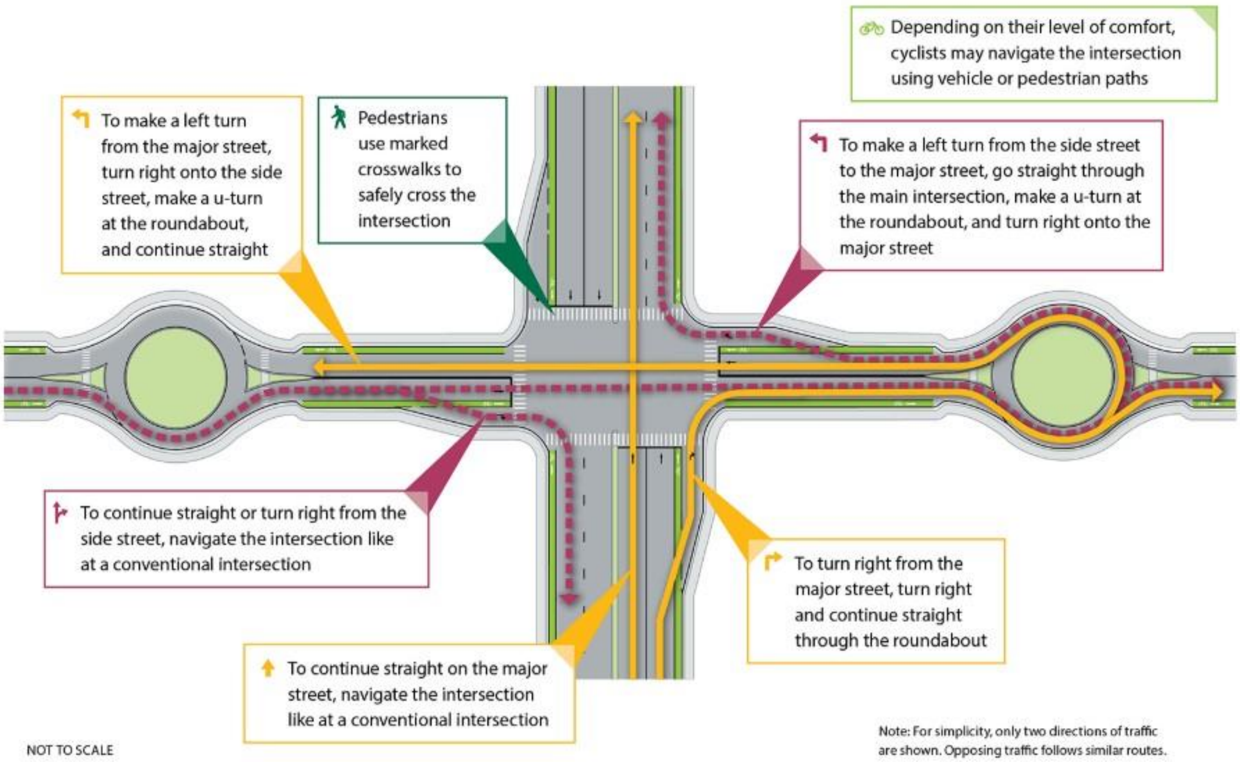
**Figure 94. Features of Typical Three-Lane Roundabout (*2*).**

Bowtie intersections restrict left turns at the main intersection by requiring left-turning vehicles to use one of two roundabouts located on each leg of the minor street (see Figure 95).

These roundabouts may have two to four legs, meaning they may simply serve the main intersection or be a smaller intersection themselves. Bowtie intersections should be considered at locations with:

- Moderate to heavy through traffic volumes and low to moderate left-turn traffic (*3*).
- Narrow or nonexistent medians and/or limited right of way to expand (*3*).

The critical aspect of this design is the removal of the left-turn movements from the main intersection. To facilitate correct traffic patterns, dedicated right-turn lanes may be used. Design of the actual roundabouts should be consistent with typical roundabout design practices.




Source: Virginia Department of Transportation (VDOT) Innovative Intersections and Interchanges, How to Navigate, Bowtie.

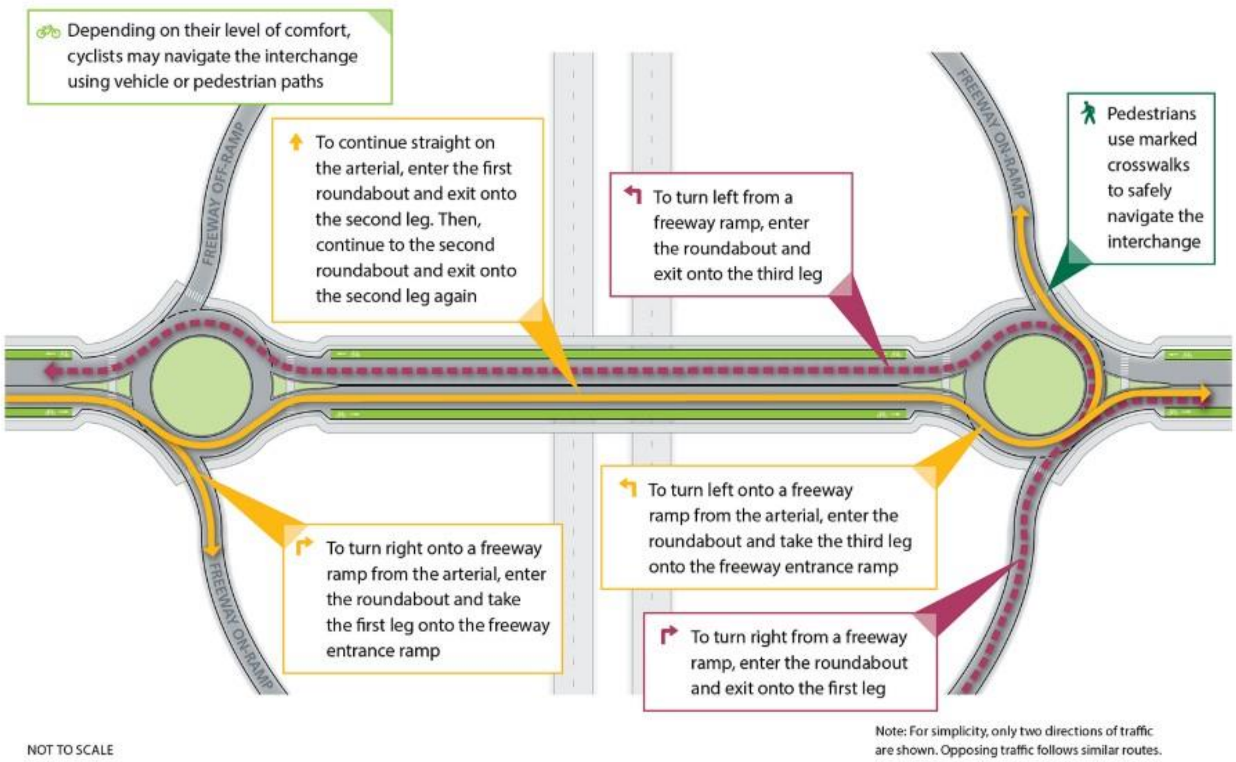
**Figure 95. Example of Bowtie Intersection (*3*).**

The interchange version of the Bowtie intersection is the dogbone or double roundabout. This design is characterized by the use of roundabouts instead of traditional intersections at the ramp terminals of a diamond interchange (see Figure 96).

Overpasses (i.e., grade separation of intersecting roads with no means of egress between them) represent an alternative to maximally reduce intersection crashes. Interchanges, rather than the alternative intersections previously discussed, combine some of the conflict reduction of overpasses with mobility between the two facilities. Dogbone interchanges could be considered at locations with:

- Heavy left-turn volumes onto the freeway ramps (3).
- Limited room between intersections for vehicles to wait at traffic signals (3).
- Heavily used off-ramp interchanges where vehicles back up on the freeway (3).

The roundabouts at a dogbone interchange typically have four legs (two two-way legs for the cross street, one ramp entry leg, and one ramp exit leg. This typical layout can be modified to have fewer or more legs depending on the access points nearby.

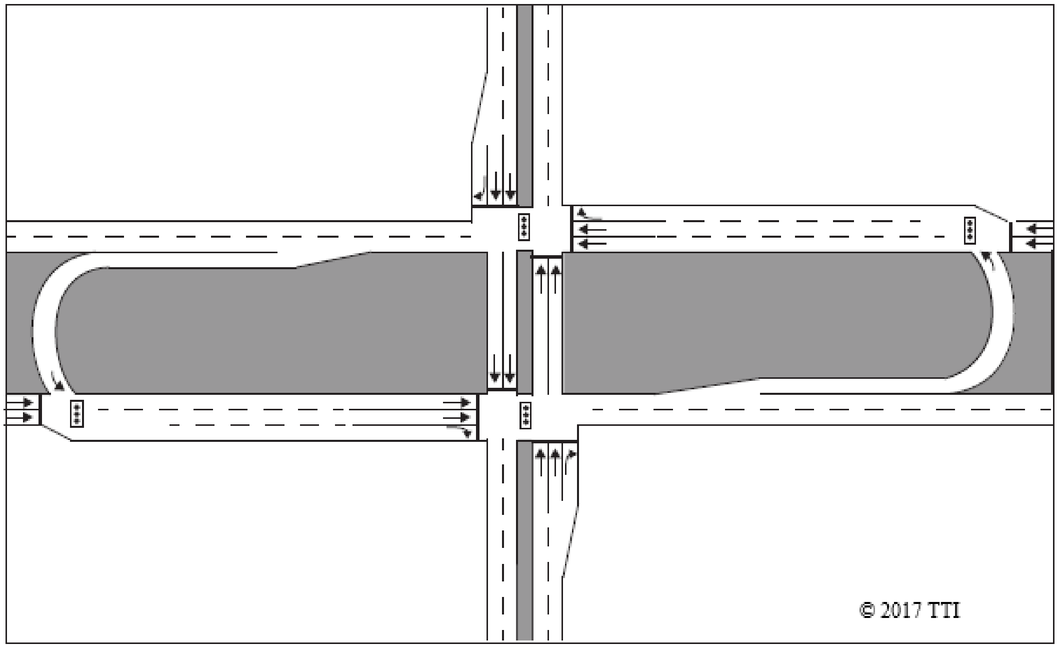



Source: VDOT Innovative Intersections and Interchanges, How to Navigate, Double Roundabout.

**Figure 96. Example of Dogbone Intersection (*3*).**

### Alternative Intersection, U-Turn-Based

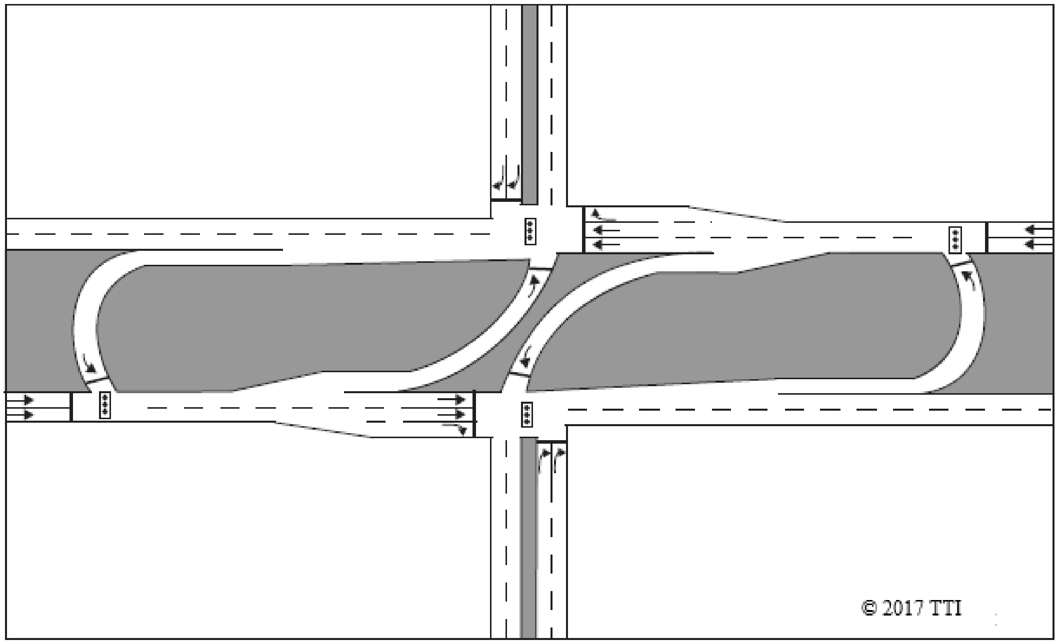
MUTs are one of several intersection types that fall under the broader category of U-turn-based intersections. MUTs replace the left-turn movements at the intersection with U-turns located a set distance from the intersection. In the MUT design, no left turns are permitted from the major or minor streets, however, minor street through movements are permitted. MUTs typically include traffic signals at the main intersection and may or may not use traffic signals at the U-turn intersections. A study by Chrysler et al. (*4*) provides a discussion of signing options for MUTs. An overview of an MUT intersection is provided in Figure 97.




Source: Texas A&M Transportation Institute.

**Figure 97. Typical MUT Configuration with Through Movement Allowed from Minor and with Signalized U-Turns.**

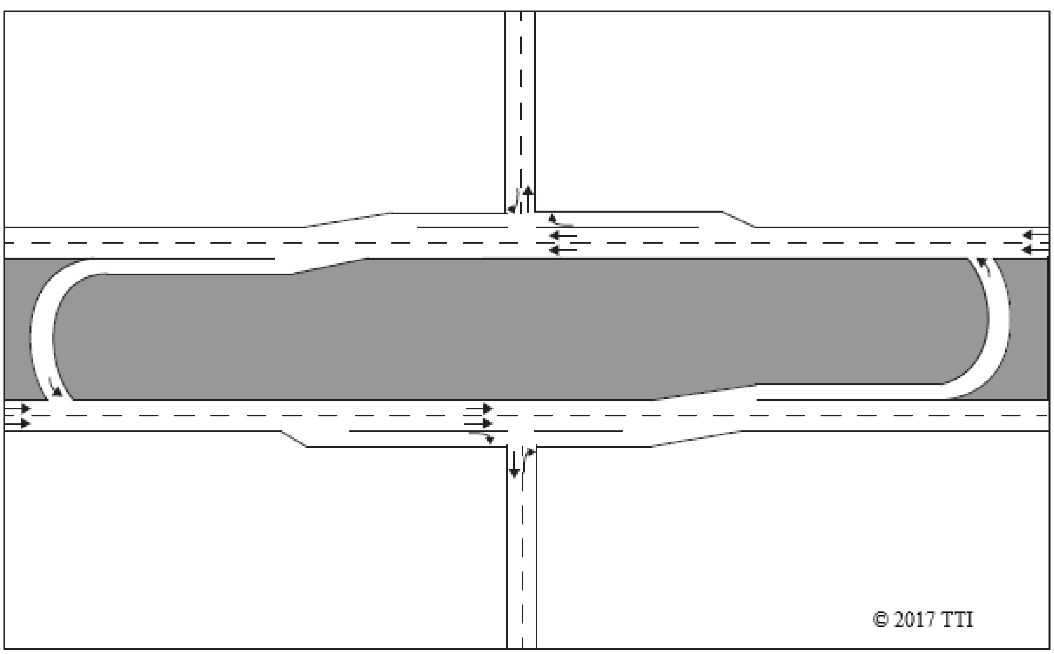
Another design in the category of U-turn-based intersections is the restricted crossing U-turn (RCUT). The RCUT design is distinguished by the presence of left-turn lanes on the major (divided) roadway and a restriction forcing all minor street traffic to turn right initially. Minor street traffic intending to go through the intersection turns right and proceeds to one of the median U-turns before turning right again at the intersection and continuing on their original path. Traffic signals are typically present at RCUT intersections. An example of an RCUT with one left-turn lane for each major approach is provided in Figure 98.




Source: Texas A&M Transportation Institute.

**Figure 98. Restricted Crossing U-Turn with a Single U-turn Lane.**

J-turns are used to refer to unsignalized RCUT intersections. The term is also used to describe intersections where all major street left turns, minor street through movements, and minor street left-turn movements are required to use the U-turns. Figure 99 depicts a J-turn.



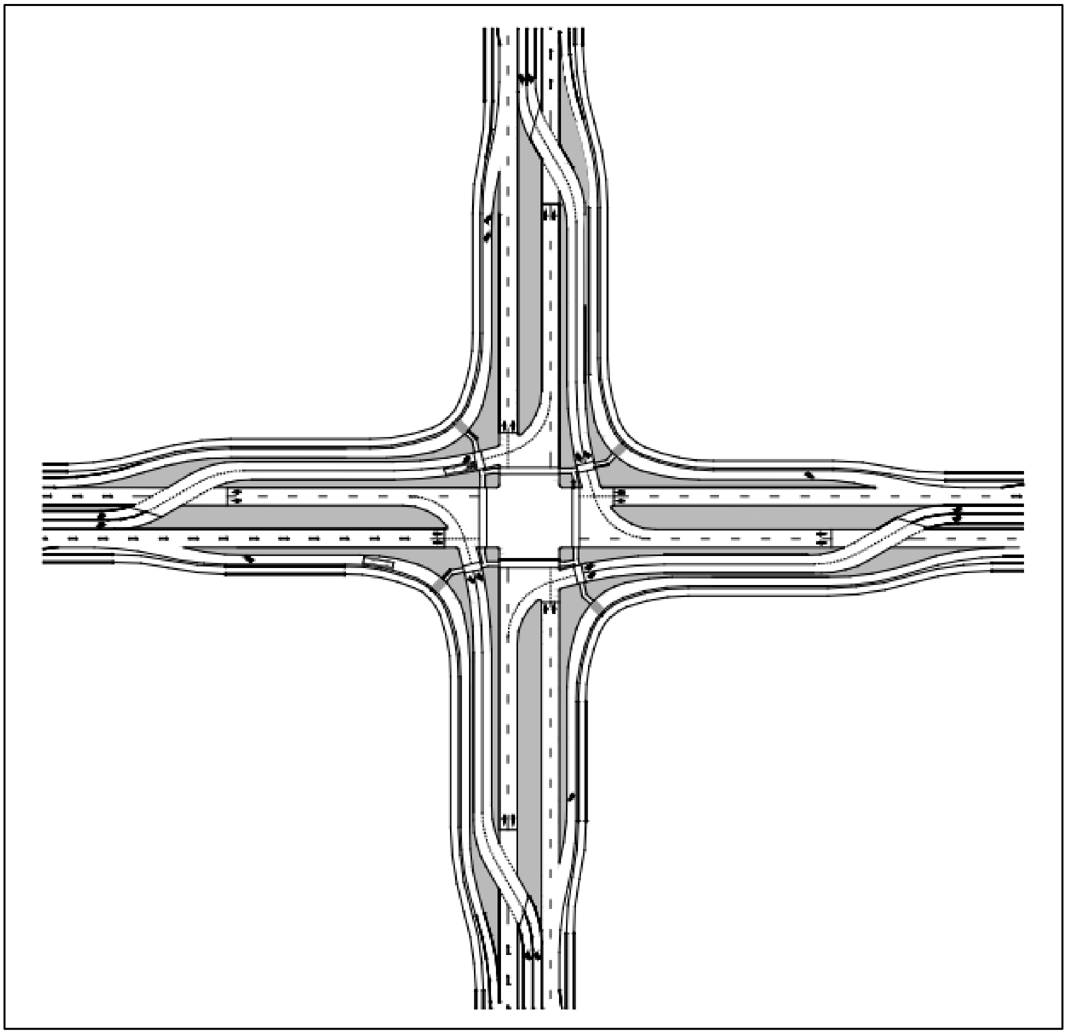

Source: Texas A&M Transportation Institute.

**Figure 99. J-Turn with a Single U-Turn Lane.**

**Alternative Intersection, Crossover-Based**

Despite the fact that the term crossover is often used to describe the U-turn intersections of U-turn-based designs, crossover-based intersections actually describe an entirely different style of design. The category of crossover-based intersections is broadly used for designs where the conventional travel patterns (i.e., driving on the right side of the road) are changed. This principle is used by several intersection designs, most notably displaced left turns (DLTs) and diverging diamond interchanges (DDIs).

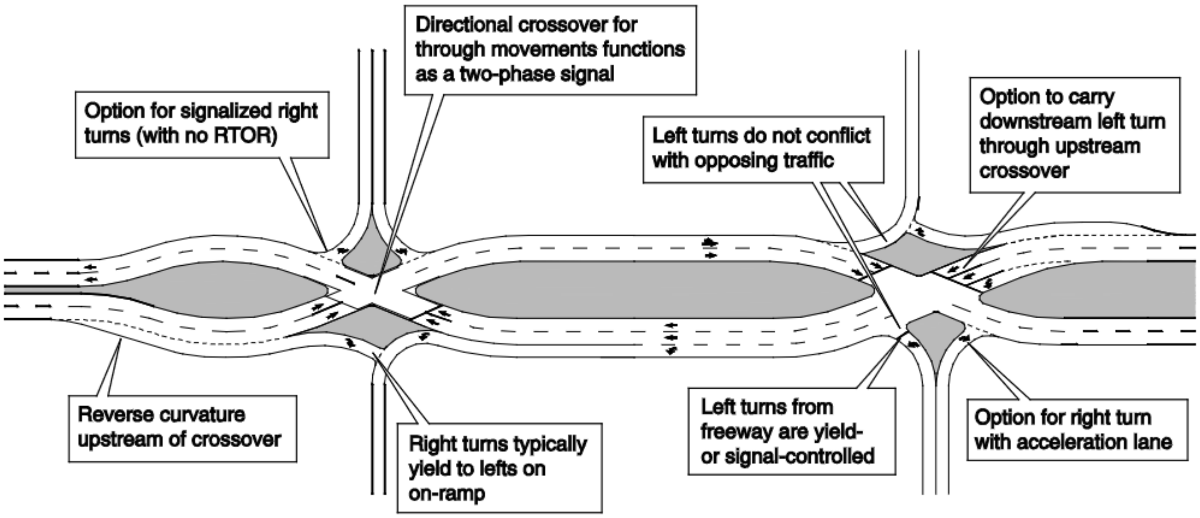
DLTs function by using crossover intersections in advance of the major intersection to move left-turning vehicles to the far side of oncoming traffic. This allows left-turning and through-movement traffic to pass through the main intersection simultaneously. The displaced left-turn lanes can be used on the major street, minor street, or both streets (*5*). An intersection with displaced left-turn lanes on all approaches is shown in Figure 100.



Source: Displaced Left Turn Informational Guide, Exhibit 1-12, Page 11.

**Figure 100. Four-Leg DLT with Displaced Lefts on All Approaches (*5*).**

DDIs are composed of two directional crossover intersections (DCIs) (*6*). Each DCI uses a two-phase signal to control traffic (*7*). The crossover intersections switch the direction of travel, removing the conflict between through and left-turning vehicles, as shown in Figure 101.




Source: Diverging Diamond Interchange Informational Guide, Exhibit 1-1, Page 4.

**Figure 101. Key Characteristics of a DDI (*7*).**

## SELECTION OF INTERSECTION TYPE

Every junction of two roadways possesses unique characteristics. Intersection Control Evaluation (ICE) provides a framework for the context-sensitive selection of intersection and interchange treatments, both geometric and traffic control devices, to use at particular locations. FHWA (*8*) describes ICE as a "data-driven, performance-based framework and approach used to objectively screen alternatives and identify an optimal geometric and control solution for an intersection." Several states have adopted ICE procedures or reference their use in various roadway design guides, including California (*9*), Florida (*10*, *11*), Georgia (*12*, *13*, *14*), Indiana (*15*), Minnesota (*16*), Nevada (*17*), Pennsylvania (*18*), Washington (*19*), and Wisconsin (*20*).

ICE typically uses two stages to identify the appropriate intersection design for specific scenarios. Stage 1 consists of scoping. The goal of this stage is to develop a short-list of possible alternatives that merit further consideration. Key questions to examine during this stage, according to FHWA (*8*), include:

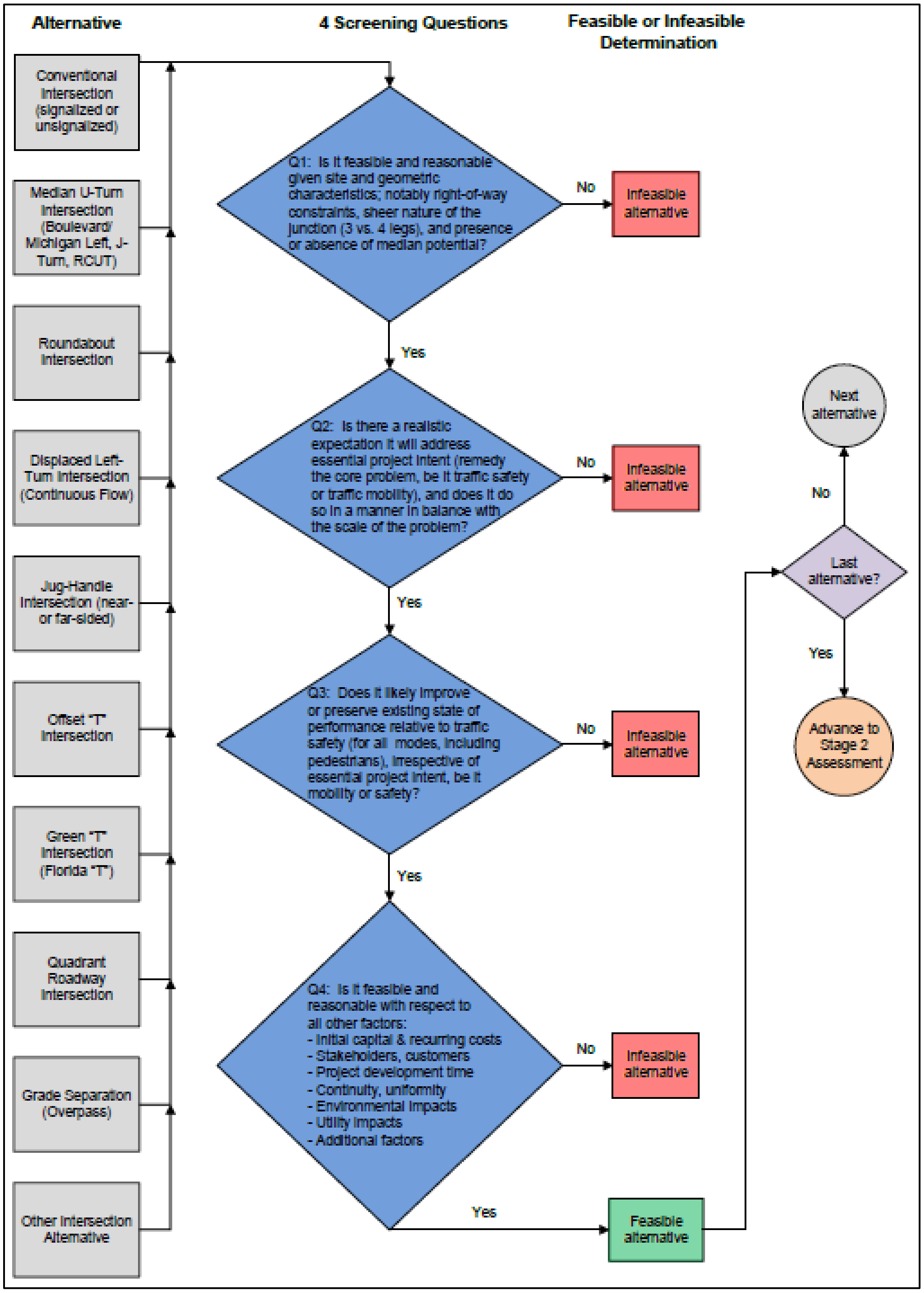
- Does the alternative meet the transportation purpose and need?
- Does the alternative address the key system performance criteria (e.g., safety, non-motorized user accommodation, operational quality, etc.)?
- Does the alternative meet the needs and values of the local community and directly affected stakeholders?

During Stage 1, four considerations are addressed: safety, operational, multimodal, and other. Collectively, the aforementioned considerations are used to develop the short-list of alternatives meriting further consideration from all possible alternatives.

Stage 2 is focused on identifying the best alternative from the short-list. The primary concerns of this stage include (*8*):

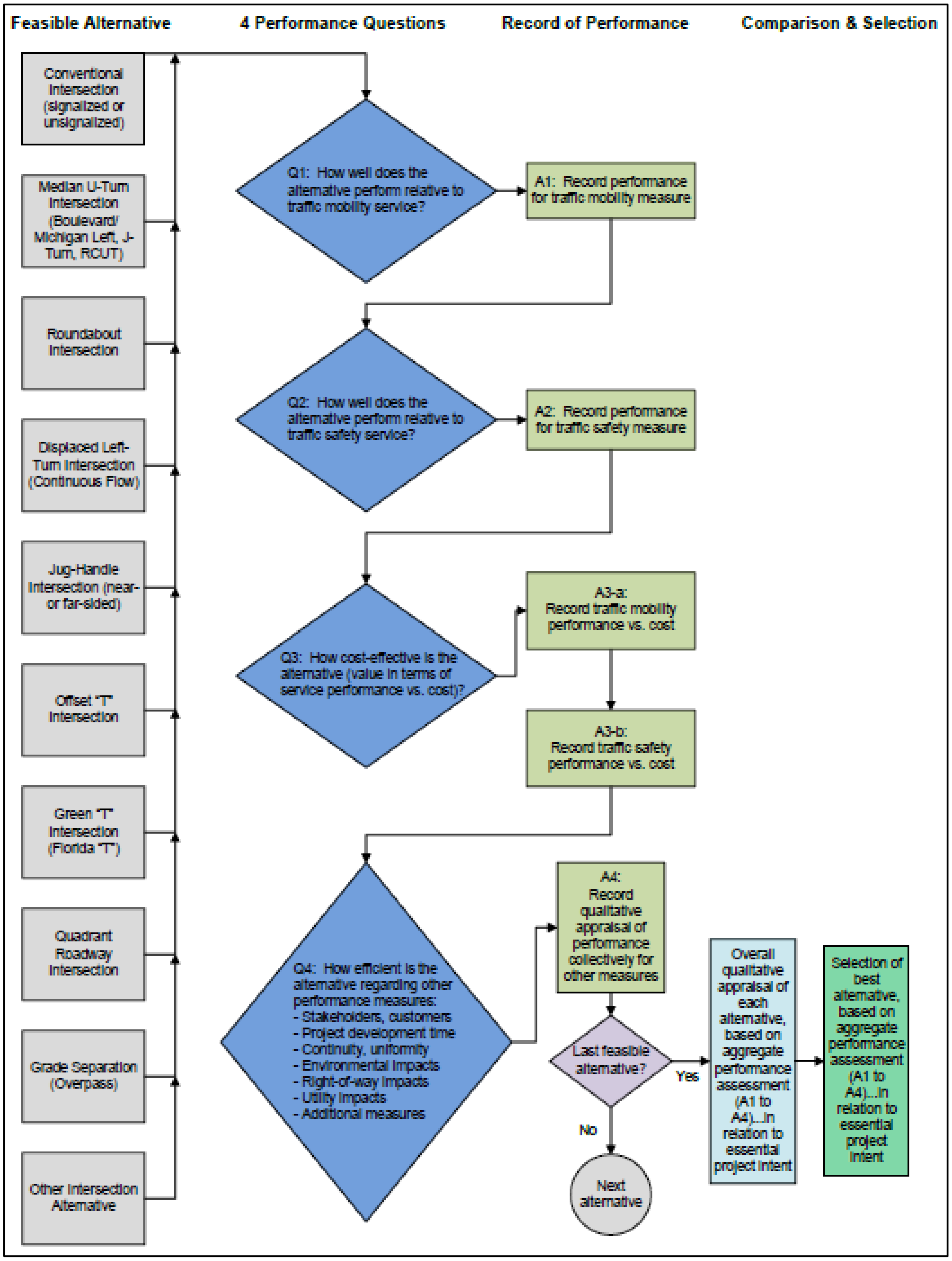
- Safety performance (motorized and non-motorized).
- Operational performance (present vs. projected, peak vs. off-peak).
- Cost.
- Benefit-cost.
- Environmental, utility, and right-of-way impacts.
- Multimodal accommodations (pedestrian, bike, transit).
- Public opinion and input.
- Other factors specific to the context (e.g., consistency with future land use, transportation plans for the surrounding area).

Indiana’s two-stage, systematic approach (*15*), illustrated in Figure 102 and Figure 103, exemplifies the data-driven methodology that defines ICE procedures.




Source: InDOT Intersection Design Guide, Stage 1, Page 6.

**Figure 102. Stage 1: Initial Feasibility Screening (*15*).**




Source: InDOT Intersection Design Guide, Stage 2, Page 7.

**Figure 103. Stage 2: Secondary, Expanded Performance Assessment (*15*).**

When applying ICE methodology, agencies are encouraged to use all analysis tools at their disposal, including the *Highway Safety Manual* (*21*), Safety Performance for Intersection Control Evaluation (*22*), *Highway Capacity Manual* (*23*), Capacity Analysis for the Planning of Junctions (*24*), and traffic simulation models. Some states have taken it upon themselves to develop tools to help facilitate the junction selection/design process. For example, Indiana has sponsored research that used microsimulation research to develop guidelines for the selection of alternative diamond interchanges, highlighting the data-driven nature of the process (*25*, *26*). Based on the number of continuous lanes on the crossing road, the number of continuous lanes on the off-ramp, the number of lanes on the off-ramp approach to the terminal intersection, and the non-freeway design hour flow rate, the best interchange for the particular situation could be selected.

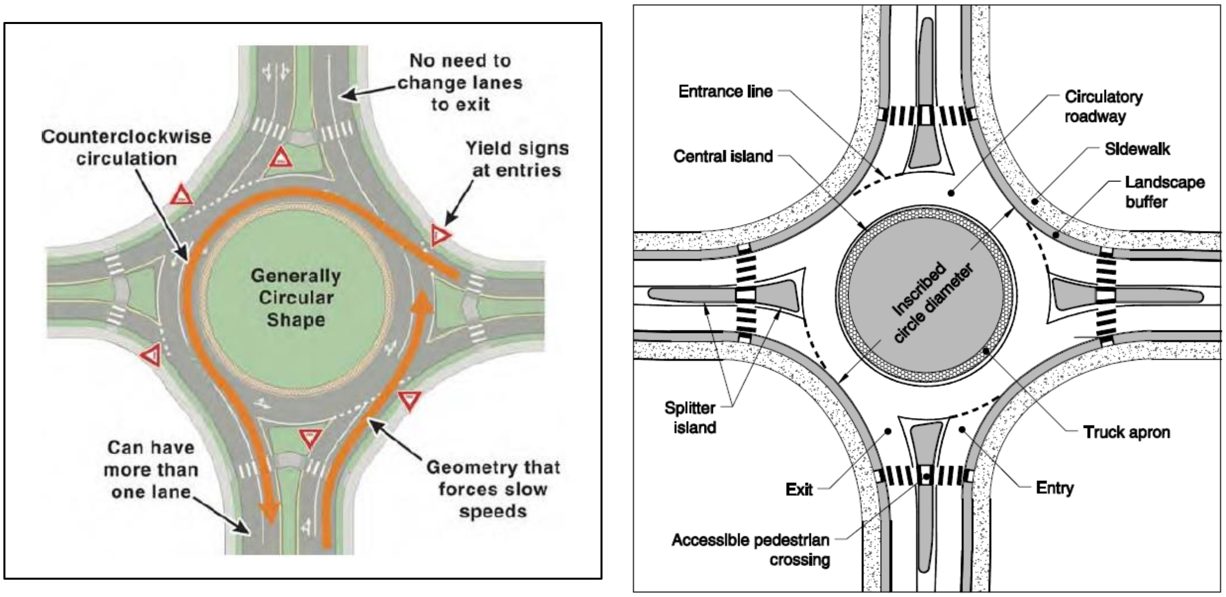
To aid in identifying potential intersection designs, Hummer (*27*) developed a safest feasible intersection design for each combination of major and minor street size and demand. Hummer also created tables to illustrate optimum feasible intersection design for pedestrians and bicyclists (*28*). The tables are dominated by four designs, including all-way stop control, roundabouts, reduced conflict intersections, and median U-turns, and reflect current knowledge in safety along with being limited to conditions reflected. The tables can give planners and designers a default concept for a particular location that could be the starting place for detailed analysis.

## DESIGN

This section provides information on geometric design features of roundabouts, U-turn-based intersections, crossover-based intersections, and selected other innovative intersection forms. These design considerations cover general principles for intersection design, and, where applicable, considerations for specific road users are also addressed.

### Roundabouts

A roundabout is a form of circular intersection in which traffic travels counterclockwise around a central island and in which entering traffic must yield to circulating traffic (*2*). Key roundabout features include a generally circular shape, yield control of entering traffic, and geometric curvature and features to induce desirable vehicular speeds. Splitter islands have multiple roles: separate entering and exiting traffic, deflect and slow entering traffic, and provide a pedestrian refuge. Figure 104 contains two drawings of a typical roundabout, annotated to identify the key characteristics, and Table 45 provides a description of each of the key features.




Source: NCHRP Report 672, Exhibit 1-1, Page 1-3, and Exhibit 6-2, Page 6-9.

**Figure 104. Key Roundabout Characteristics and Basic Geometric Elements (2).**

**Table 45. Description of Key Roundabout Features (*2*).**

| 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 | A splitter island is a 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. |
| Apron | An 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 Americans with Disabilities Act requirements. |
| Landscape Buffer | Landscape buffers separate vehicular and pedestrian traffic and assist with guiding pedestrians to the designated crossing locations. This feature is particularly important as a wayfinding cue for individuals who are visually impaired. Landscape buffers can also significantly improve the aesthetics of the intersection. |

Source: Adapted from NCHRP Report 672, Exhibit 1-2, Page 1-4

Roundabouts can be separated into three basic categories according to size and number of lanes to facilitate discussion of specific performance or design issues: mini-roundabouts, single-lane roundabouts, and multilane roundabouts. Separate categories are not explicitly defined for rural, urban, and suburban areas. Roundabouts in urban areas may require smaller inscribed circle diameters (ICDs) due to smaller design vehicles and existing right-of-way constraints, and they may also include more extensive pedestrian and bicycle features. Roundabouts in rural areas typically have higher approach speeds and thus need special attention to visibility, approach alignment, and cross-sectional details. Suburban roundabouts may combine features of both urban and rural environments. Table 46 summarizes and compares some fundamental design elements and recommended values for each of the three roundabout categories. Additional description and discussion of each category can be found in NCHRP Report 672, which also serves as FHWA's *Roundabouts: An Informational Guide* (*2*), from which Table 46 and the related discussion is obtained.

**Table 46. Comparison of Design Elements in Roundabout Categories (*2*).**

| **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 |

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

Source: Adapted from NCHRP Report 672, Exhibit 1-9, Page 1-12

As in any roadway design process, there are trade-offs among certain aspects such as operations, safety, capacity, cost, right-of-way, etc. A design that favors one aspect may negatively affect another one. For example, there are trade-offs in accommodating large trucks on the roundabout approach and entry while maintaining slow design speeds. Increasing the entry width or entry radius to better accommodate a large truck may also increase the speeds of vehicles entering the roundabout. Therefore, designers must balance these competing needs and may need to adjust the initial design parameters. To both accommodate the design vehicle and maintain lower speeds, additional design modifications could be required, such as offsetting the approach alignment to the left or increasing the inscribed circle diameter of the roundabout.

Roundabouts where higher speeds and/or larger vehicles are expected, particularly located in rural or industrial environments, also have design trade-offs. Rural areas typically have higher approach speeds than for urban or local streets, and drivers do not expect to encounter speed interruptions. Industrial or manufacturing areas, and even some freeway interchanges, particularly interchanges with a high proportion of left-turn movements during peak periods and limited queue storage space, tend to carry more large trucks or oversize/overweight (OSOW) vehicles, thus needing to accommodate larger design vehicles. A familiarity with existing design guidance helps a designer better understand all of these issues and potential solutions.

Roundabout design can be thought of as an iterative process where a variety of design objectives must be considered and balanced within site-specific constraints. Maximizing operational performance and safety for a roundabout requires the designer to think through the design rather than rely upon a design template. Many of the geometric elements have ranges of typical values for guidance in the design of individual roundabout components. The use of a design technique not explicitly included in this document or a value that is outside of a range of typical values does not automatically create an unacceptable design, provided that the design principles can be achieved.

Designers should consider several overarching principles to guide the development of all roundabout designs. Achieving these principles should be the goal of any roundabout design (*2*):

- Provide slow entry speeds and consistent speeds through the roundabout by using deflection.
- Provide the appropriate number of lanes and lane assignment to achieve adequate capacity, lane volume balance, and lane continuity.
- Provide smooth channelization that is intuitive to drivers and results in vehicles naturally using the intended lanes.
- Provide adequate accommodation for the design vehicles.

- Design to meet the needs of pedestrians and cyclists.
- Provide appropriate sight distance and visibility for driver recognition of the intersection and conflicting users.

*Slow Entry Speeds*

The most important design objective for roundabouts is to maintain low and consistent speeds throughout the roundabout. The operating speed of a roundabout is widely recognized as one of its most important attributes in terms of safety performance (*29*). Maximum entering design speeds based on a theoretical fastest path of 20 to 25 mph (32 to 40 km/h) are recommended at single-lane roundabouts and 25 to 30 mph (40 to 48 km/h) at multilane roundabouts (*2*). Strategies to transition drivers from higher speeds on the approach to lower speeds in the roundabout entry include how the following are designed: inscribed circle diameter, splitter island, approach alignment, and curbing.

*Inscribed Circle Diameters*

A roundabout needs an appropriate balance between the need to accommodate the design vehicle, which could be a large truck that needs a larger radius, and the need to keep speeds relatively low. It is recommended that ICDs not exceed 200 ft, with typical ICDs at 180 ft or less, even for roundabouts with high-speed approaches, because the larger curves can encourage higher speeds while maneuvering through the roundabout. However, within that limit on ICD, recent research on roundabouts for high-speed and rural locations (*30*) indicates that a larger ICD is related to lower delay for roundabouts with OSOW vehicles and large percentages of trucks. In that research, a roundabout with a 180-ft ICD had the lowest delay compared to ICDs of 150 ft and 120 ft, and the 120-ft ICD roundabout had a lower capacity and level of service than the larger roundabouts.

Urban and suburban roundabouts will typically be smaller than rural roundabouts, both to accommodate right-of-way constraints and to reflect an environment with generally lower speeds. A larger ICD can reduce the angle between approaching and circulating vehicles, which can contribute to reductions in crash severity, but higher speeds can mitigate that benefit. In short, the size must be appropriate for conditions and not increase the frequency or severity of other types of crashes.

A roundabout with a larger diameter may have a larger footprint but may be required to accommodate large trucks while providing increased visibility and speed control. However, in some cases, land constraints may limit the ability to accommodate large semi-trailer combinations while achieving adequate deflection for small vehicles. In such situations, a truck apron may be used to provide additional traversable area around the central island for large semi-trailers. Where provided, truck aprons should be designed with a curbed edge high enough (typically 2–3 inches) to discourage passenger vehicles from traversing over the top of the apron (*2*).

*Splitter Islands*

Splitter islands should be provided on every approach to single-lane and multilane roundabouts. They serve several important purposes for operational and safety performance, including the following:

- Provide a visual cue for approaching drivers.
- Separate opposing lanes of vehicle traffic.
- Assist in controlling vehicle speeds.
- Provide refuge for crossing pedestrians.
- Guide vehicle traffic into the appropriate path through the roundabout.
- Deter wrong-way movements.

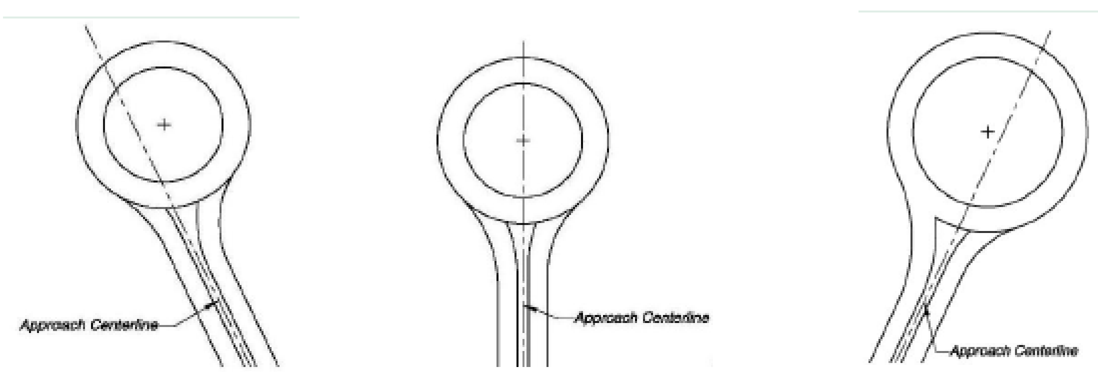
The total length of the raised island should generally be at least 50 ft, although 100 ft is desirable, to provide sufficient protection for pedestrians and to alert approaching drivers to the geometry of the roundabout. For high-speed approaches, the length of the splitter island is extended, with a recommended length of 200 ft.

*Approach Alignment*

Roundabout design requires balancing and optimizing three design considerations to incorporate the design principles mentioned previously. Those design considerations are size, position, and approach alignment. Site constraints, appropriate vehicle speeds, and accommodation of the design vehicle are all factors in how to optimize those considerations. Size is related to the ICD, while position and approach alignment are related to each other. The position of the roundabout at the intersection helps to determine the alignment of the approaches;

if the roundabout is centered on the point of intersection, then the approach alignment may be relatively simple (with the necessary deflection at the yield line to help reduce speeds and align approaching vehicles with the appropriate path into and through the roundabout). If the roundabout is shifted away from the point of intersection, then the approach alignments will also be shifted to match. Shifting the roundabout and/or the approach alignments can be useful in encouraging the proper reduction in speed, accommodating the design vehicle, and improving visibility to adjacent legs of the intersection.

Three categories of approach alignments are center, offset left, and offset right. Center alignment has the extended centerline of the alignment passing through the center of the roundabout. Correspondingly, offset left has the approach centerline to the left of the roundabout's center and offset right to the right, as shown in Figure 105. More details and related diagrams can be found in NCHRP Report 672 (*2*).




Offset Left Center Offset Right

**Figure 105. Roundabout Entry Alignment Alternatives (adapted from Exhibit 6-10 in *2*).**

Providing an offset-left approach alignment increases the deflection and allows for slower entry speeds (*2*). It is also beneficial for accommodating large trucks with a small ICD since it allows for larger entry radius while maintaining deflection and speed control. A left offset is preferred for high-speed approaches. The potential tradeoff is that the exit design may require much larger radii, ranging from 300 to 800 ft or greater. However, larger exit radii may also be desirable in areas with high truck volumes to provide ease of navigation for trucks and reduce the potential for trailers to track over the outside curb (*2*).

Particularly for high-speed approaches, approach curves can also help to notify the driver of an upcoming change in conditions and encourage drivers to reduce speeds to an appropriate level. Roundabouts on high-speed facilities, even with extra signing efforts, may not be expected by approaching drivers, resulting in erratic behavior and an increase in single-vehicle crashes. All high-speed approaches should include speed reduction treatments, such as horizontal curvature. Depending on the approach alignment, one curve or successive reverse curves may be appropriate to reduce approach speeds and align the approaching vehicle with the appropriate path into the roundabout. Approach curves should be designed so that each curve and the central island are visible to drivers before they reach the first curve.

*Curbing*

Curbs are typically provided in urban and suburban (and/or low- to moderate-speed) locations, and roundabout curbing generally matches the adjacent approaches. Rural/high-speed roadways typically do not have curbs, but for roundabouts curbs should be provided on all approaches on high-speed facilities to alert drivers of a change in the driving environment (*2*). Consideration should also be given to reducing shoulder widths. Curbs help to improve delineation and to prevent corner-cutting, which helps to ensure low speeds. In this way, curbs help guide vehicles to the intended design path. The designer should carefully consider all likely design vehicles, including farm equipment, when setting curb locations for rural roundabouts.

Because roundabouts are intentionally designed to slow traffic, narrow curb-to-curb widths and tight turning radii are typically used; however, if the widths and turning requirements are designed too restrictively, they may not accommodate large vehicles. Large trucks and buses often control many of the roundabout's dimensions, particularly for single-lane roundabouts. Truck aprons can help provide additional space for large vehicles while still discouraging high speeds from passenger cars.

*Design Vehicle Accommodation*

The location of the roundabout may govern the specific design vehicle selected. Recreational routes are often frequented by motor homes and other recreational vehicles. Agricultural areas are frequented by tractors, combines, and other farm machinery. Manufacturing areas may see OSOW trucks. The design process needs to consider the selection of an appropriate design vehicle as an early step so that design elements can be properly dimensioned to accommodate that vehicle.

*Visibility*

A critical feature affecting safety at intersections, particularly rural intersections, is the visibility of the intersection. Roundabouts are similar to stop-controlled or signalized intersections in rural or high-speed environments except for the presence of curbing along roadways that are typically not curbed. Single-vehicle crashes can be minimized with enhanced visibility of the roundabout and its approaches. The geometric alignment of approach roadways should be constructed to maximize the visibility of the central island and the shape of the roundabout whenever possible. Where sufficient visibility cannot be provided through geometric alignment then additional treatments such as signing, pavement markings, or advance warning beacons should be considered similar to those that would be applied to rural stop-controlled or signalized intersections.

Visibility of the other approaches should emphasize the adjacent approach in either direction so that approaching drivers can see any conflicting traffic arriving from their left and so that they can be seen by downstream drivers on their right. For a traditional four-leg, 90-degree intersection, it is not as critical for approaching drivers to see the approach directly across from them as it is to see what is to their right and left. In fact, depending on the terrain and the isolation of the intersection, it may be preferable to include a landscape feature in the central island to provide a visual cue to the approaching driver that there is a change in environment for which they need to adjust.

Landscaping in the central island can provide a visual identity of the roundabout location to drivers approaching from a distance. This landscaping of the central island can block the sight line of the approaching driver so that the driver only sees the island and not the roadway past the roundabout, encouraging a driver to focus on the adjacent approaches and making adjustments to enter and navigate the roundabout.

*Sight Distance*

Roundabouts must be designed to provide the same approach sight distance as other intersections. The approach alignment must provide a good view of the splitter island, the central island, and, preferably, the circulating roadway. The alignment must also provide adequate sight distance for passenger car drivers to detect an acceptable gap of 4 to 5 seconds for detecting potential conflicting movements with vehicles entering from the approach immediately to the left and vehicles traveling in the circulating lanes. Designers can choose to check the sight triangle for a driver to detect potential conflicts long before reaching the yield line. For roundabouts with a high volume of large trucks, the stopping sight distance for trucks (with its corresponding sight triangle) should be provided. Illustrated examples of stopping sight distance and intersection sight distance for roundabouts can be found in Exhibit 6E-17 in the Minnesota Department of Transportation (MnDOT) Facility Design Guide (*31*).

*Speed Reduction Countermeasures*

While speed reduction should be achieved through appropriate design of the roundabout approach, sites where drivers approach at excessive speeds may necessitate the use of additional speed reduction treatments. Those treatments include advance signs with and without beacons, pavement markings, illumination, speed-activated signs, and transition zones. The determination on whether to include one or more of these treatments should include information on the treatments' relative effectiveness, potential costs of installation and maintenance, and a speed study to determine the speed characteristics of the site under consideration (*32*).

*Pedestrian Considerations*

At roundabouts where pedestrian access is provided, pedestrian design provides accommodation with crosswalks around the perimeter of the roundabout, through the splitter island on each approach. By providing space to wait at the splitter island, this design functions as a median refuge island, where pedestrians can consider one direction of conflicting traffic at a time, which simplifies the task of crossing the street. Roundabouts should be designed to discourage pedestrians from crossing to the central island using treatments such as landscape buffers on the corners.

The preferred placement of crosswalks is set back from the yield line by at least one vehicle length. This shortens the pedestrian crossing distance across the roadway, helps to separate the vehicle-to-vehicle and vehicle-to-pedestrian conflict points, and allows approaching drivers to focus on only one crossing at a time (i.e., the driver at the yield line can devote attention to approaching vehicles and identifying a suitable gap, and the second driver watches for pedestrians while waiting for the first driver).

*Bicycle Considerations*

In general, cyclists who have the knowledge and skills to ride effectively and safely on roadways can navigate low-speed single-lane roundabouts without much difficulty because typical on-road bicycle speeds are similar to those found in roundabouts. The most experienced and skilled on-road cyclists will be comfortable traveling through all roundabouts like motor vehicles, even at multilane roundabouts. Some cyclists who are less comfortable riding in the street will choose to ride on sidewalks and behave like "rolling pedestrians;" for those road users, typical pedestrian treatments generally provide the necessary accommodation. Designers should check applicable local ordinances to determine if bicycles are prohibited from using sidewalks when developing the bicycle treatments for a particular intersection.

**U-Turn-Based Intersections**

U-turn-based intersections are located where one or more intersecting roads is a median-divided highway and include MUTs, RCUTs, and J-turns. These designs reasonably fit when the median width is at least 60 feet, although off-tracking of WB-67 vehicles can still occur (*33*) and should be avoided or modified when median widths are narrower than 60 feet (*34*, *35*). Strategies when median width is inadequate to accommodate the design vehicle include the following: use U-turn designs that allow larger vehicles to turn onto the shoulder or into loons, widen the median for a short distance, have more through lanes, or provide median openings for smaller vehicles and use signs to prohibit large vehicle use (*35*, *36*).

*MUTs*

With no left-turn movements present at the main intersection, the traffic signal can typically be timed using two signal phases (*37*), although specific situations and traffic volume imbalances may require more phases. Care should be taken to ensure progression between the U-turn intersections, the main intersection, and adjacent traffic signals. MUTs function best under the following conditions:

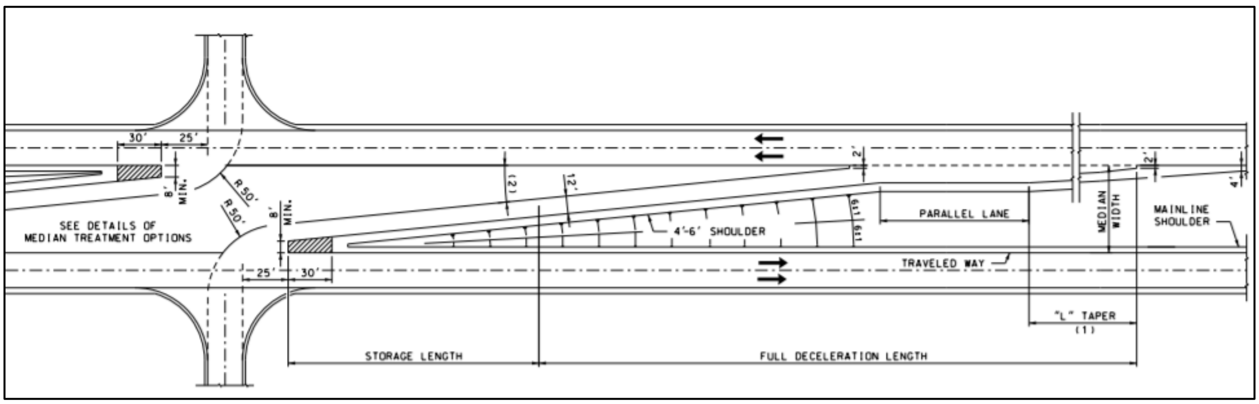
- Moderate to heavy arterial through-traffic volumes (*3*, *34*, *35*).
- Low to moderate left-turn traffic volume (*3*, *35*).
- Almost all levels of volume combinations of major and minor through traffic with low left-turning traffic (*35*, *38*).

*RCUTs*

The signal timing for RCUTs can be done in two phases (*37*) (i.e., major road through movements, simultaneous movement of major road left-turn movements and minor road movements) or split phasing could be used depending on directional volumes. They function best under the following conditions:

- 50/50 directional split on the main street for most of the day (*34*, *35*).
- Heavy through and/or left-turn traffic volumes on the major street (*3*).
- With low through and left-turn volumes on the side street (*3*, *35*).

Again, coordination between the main intersection, U-turn intersections, and adjacent traffic signals must be considered. The primary consideration of RCUTs (and J-turns) is the left-turn lane, which is not present at MUTs. The general configuration used in Missouri is shown in Figure 106 (*39*).




Source: Missouri Department of Transportation (MoDOT) Standards and Specifications, Type IV Median Opening, Sheet 1 of 1.

**Figure 106. Missouri Typical Left-Turn Lane Design of an RCUT/J-Turn (*39*).**

The left-turn lane design consists of two parts: deceleration length and storage length (*39*). The storage length is determined by traffic analysis, while the deceleration length is based on the speed of the corridor (as shown in Table 47) and includes the taper (which should use a departure rate of 15:1), the parallel lane, and additional length up to the storage lane.

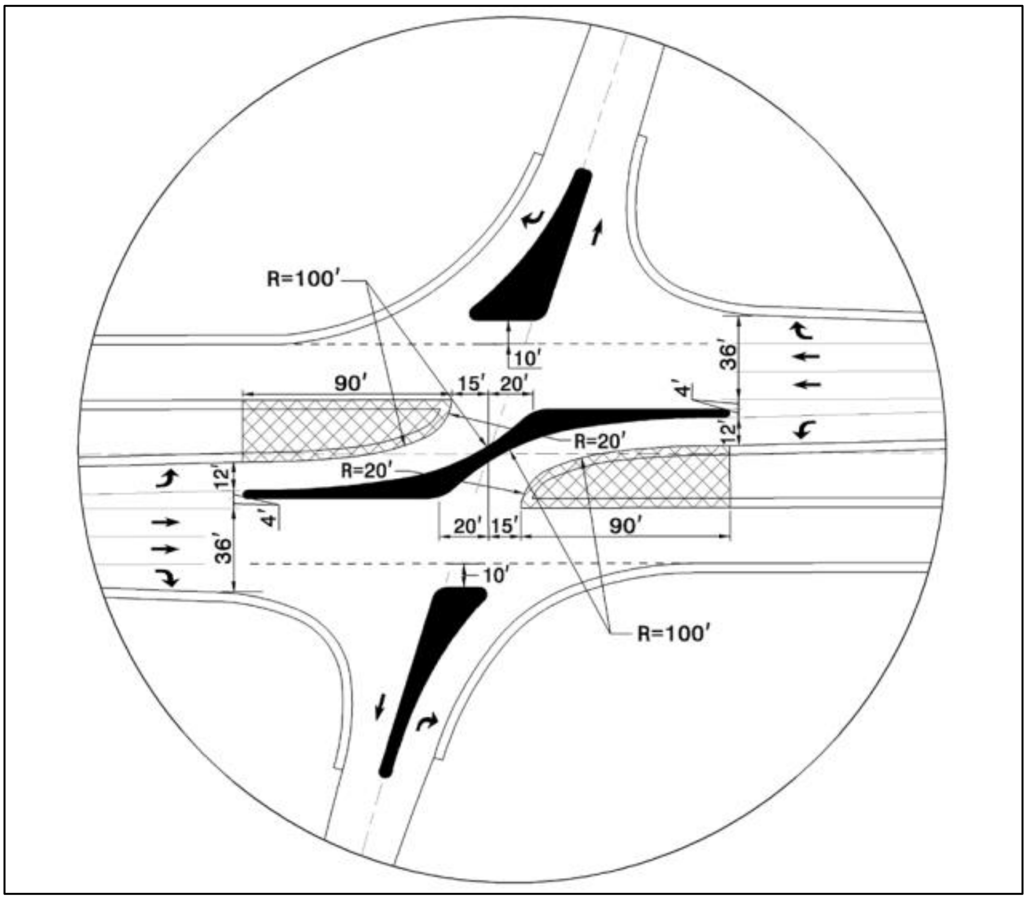
**Table 47. Full Deceleration Length (*39*).**

| Design Speed (mph) | Minimum Length (ft) |
|---|---|
| 45 | 385 |
| 50 | 435 |
| 55 | 480 |
| 60 | 530 |

| | |
|---|---|
| 65 | 570 |
| 70 | 615 |

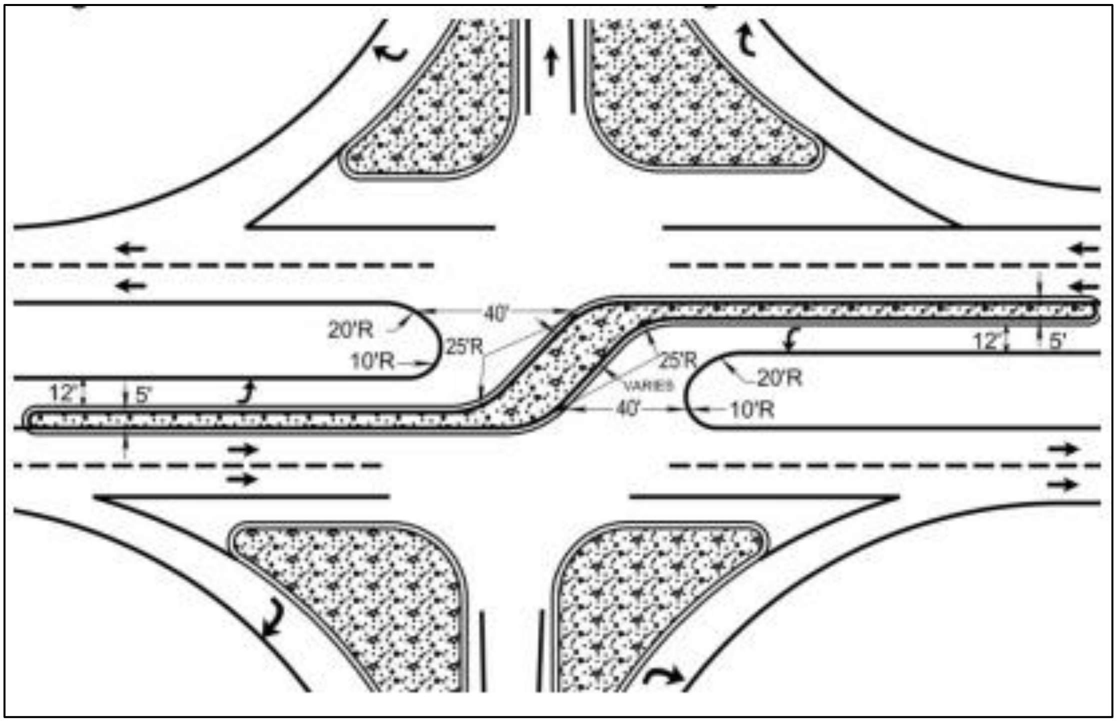
Source: MoDOT Standards and Specifications, Type IV Median Opening, Sheet 1 of 1.

The departure angle of the left-turn lane relative to the parallel lane should be 2–6 degrees. The design of the left-turn lane then plays a role in the layout of the main intersection. Different designs of the main intersection exist, potentially due to the desire to incorporate right-turn lanes at the main intersection or due to median or right-of-way availability, such as the design from North Carolina Department of Transportation (NCDOT) shown in Figure 107 (*40*) and designs from Mississippi (*41*) shown in Figure 108 through Figure 111.



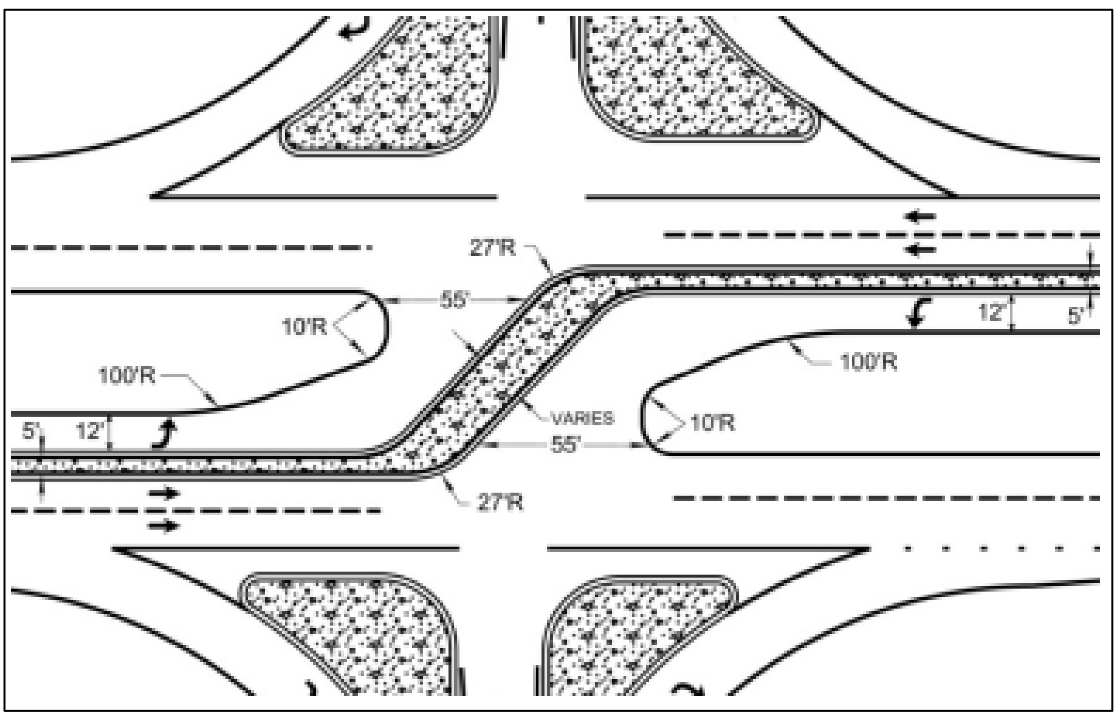

Source: NCDOT *Roadway Design Manual* Chapter 9, Inset "B", Page 41.

**Figure 107. North Carolina Main Intersection Design (*40*).**



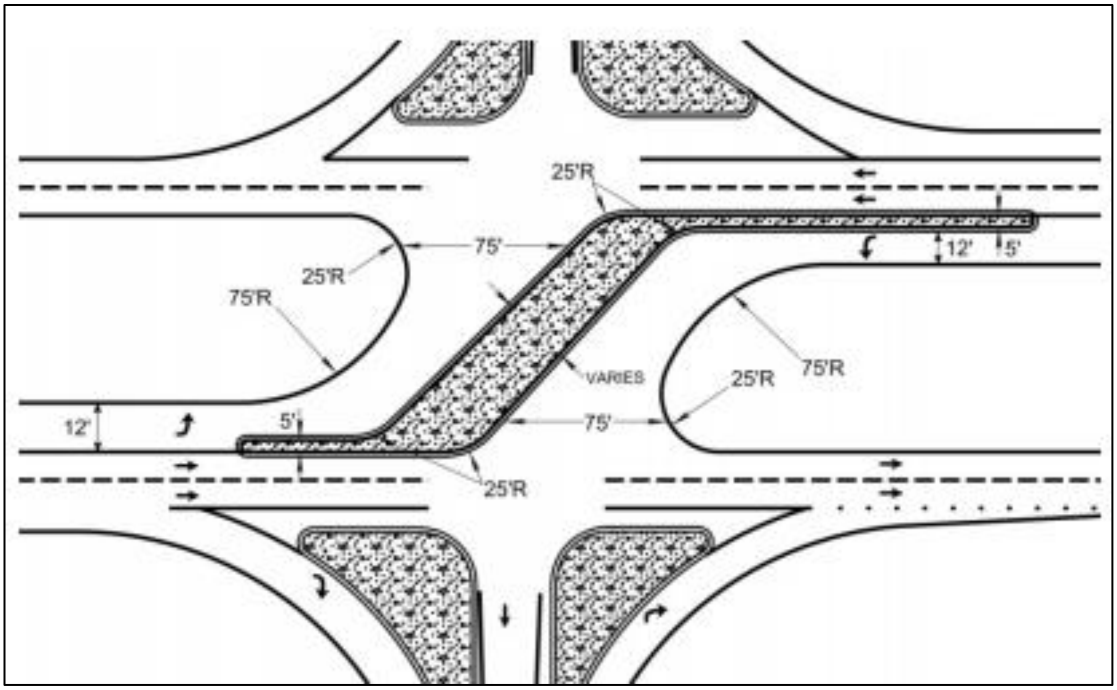

Source: Synthesis of J-Turn Design Standards and Criteria, Figure 7, Page 9.

**Figure 108. Recommended Main Intersection Design Detail for 40-ft Medians (*41*).**



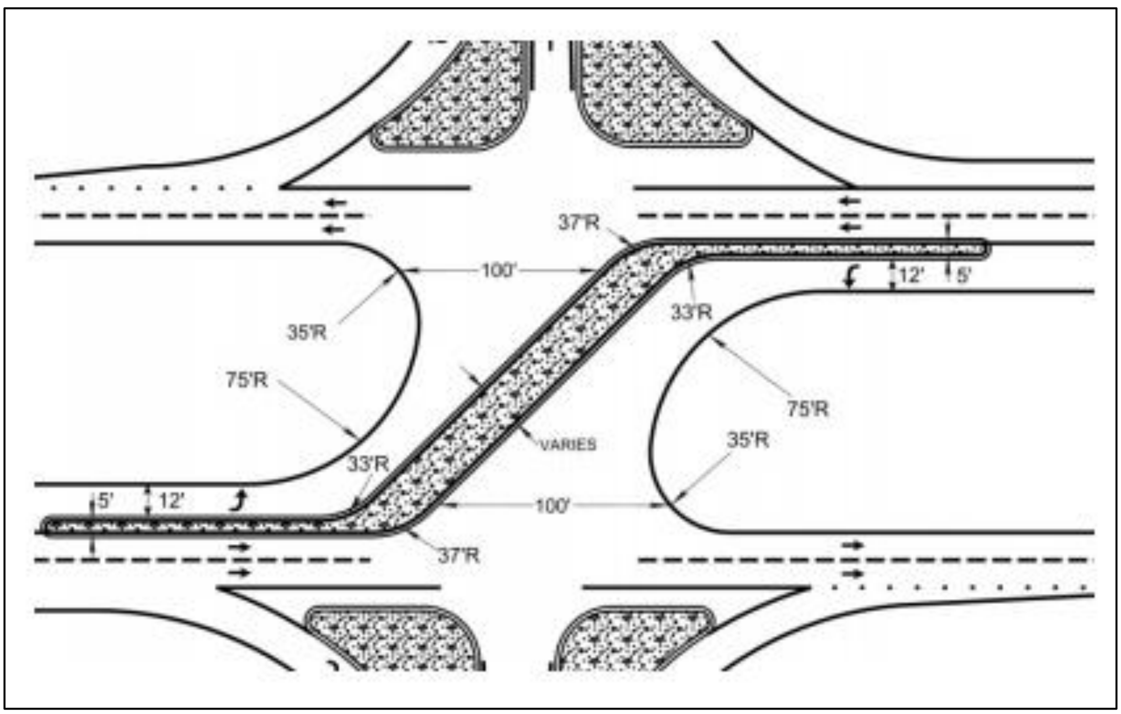

Source: Synthesis of J-Turn Design Standards and Criteria, Figure 8, Page 9.

**Figure 109. Recommended Main Intersection Design Detail for 64-ft Medians (*41*).**




Source: Synthesis of J-Turn Design Standards and Criteria, Figure 9, Page 10.

**Figure 110. Recommended Main Intersection Design Detail for 101-ft Medians (*41*).**




Source: Synthesis of J-Turn Design Standards and Criteria, Figure 10, Page 10.

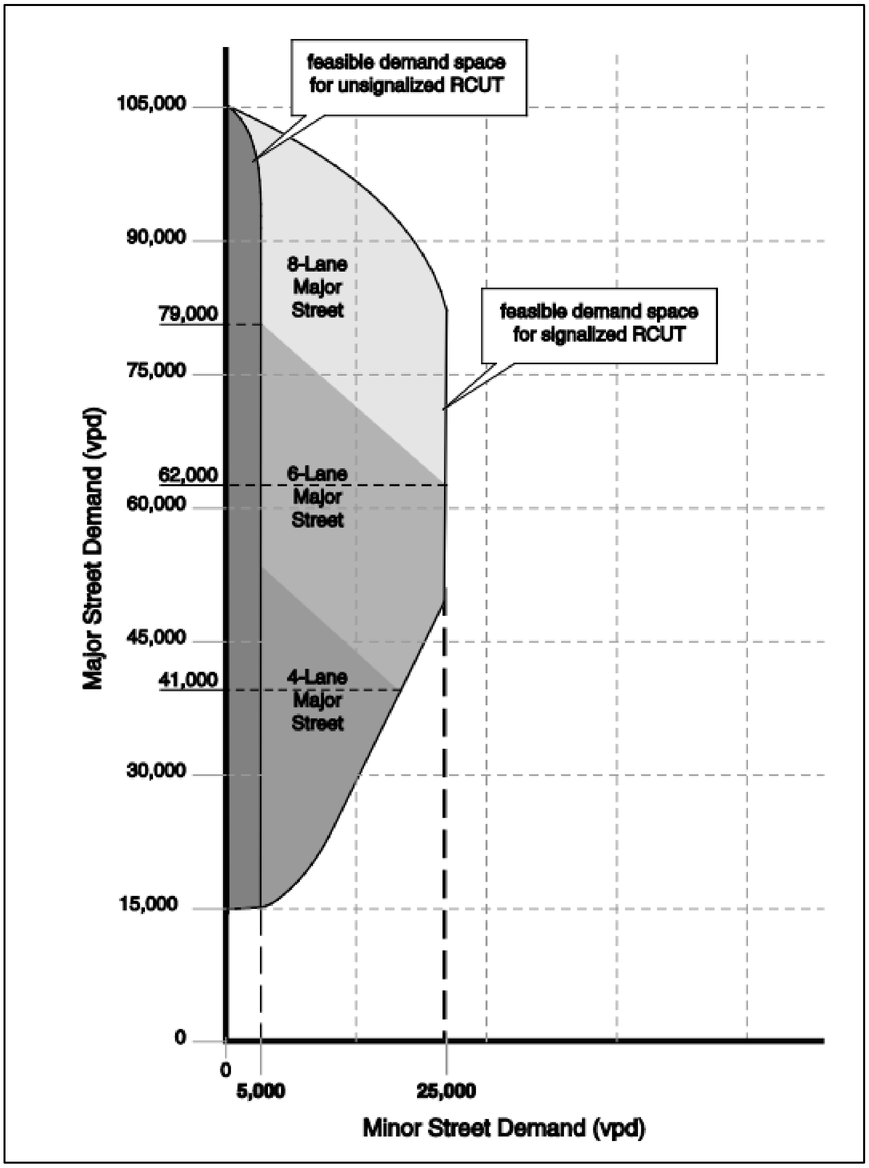
**Figure 111. Recommended Main Intersection Design Detail for 126-ft Medians (*41*).**

*J-Turns*

The largest design consideration for J-turns is the determination as to whether major road left-turn lanes need to be present and whether stop or yield control is appropriate at the U-turn intersections. The geometry of the J-turn main intersection is the same as the RCUT main intersection illustrated in Figure 107 through Figure 111. J-turns work best under the following conditions:

- Relatively low to medium side-street volumes and heavy left-turn volumes from the major road (*41*).
- Minor road total volume to total intersection volume ratio is less than or equal to 0.20 (*41*).
- Intersections that experience a high number of far-side right-angle collisions (*41*).
- Intersections where minor road crossing traffic gap times are insufficient to complete the maneuver safely and cause multiple vehicles to stack into the median opening (*41*).

To aid in the selection of RCUTs and J-turns, FHWA (*42*) has developed Figure 24 to illustrate the traffic volumes when RCUT intersections are feasible as well as when J-turns should be used. A summary of when each U-turn-based intersection design is most appropriate can be found in Table 48.




Source: Restricted Crossing U-Turn Informational Guide, Exhibit 5-7, Page 75.

**Figure 112. Feasible Demand Space for Signalized RCUT Intersection (*42*).**

**Table 48. Appropriate Scenarios for Use of U-Turn-Based Intersections.**

| MUTs | RCUTs | J-Turns |
|---|---|---|
| Moderate to heavy arterial through-traffic volumes (*3, 34, 35*). | 50/50 directional split on main street for most of the day (*34, 35*). | Relatively low to medium side-street volumes and heavy left-turn volumes from the major road (*41*). |
| Low to moderate left-turn traffic volume (*3, 35*). | Heavy through and/or left-turn traffic volumes on the major street (*3*). | Minor road total volume to total intersection volume ratio is less than or equal to 0.20 (*41*). |
| Almost all levels of volume combinations of major and minor through traffic with low left-turning traffic (*35*, *38*). | Low through and left-turn volumes on the side street (*3, 35*). | Intersections that experience a high number of far-side right-angle collisions (*41*). |
| — | — | Intersections where minor road crossing traffic gap times are insufficient to complete the maneuver safely and cause multiple vehicles to stack into the median opening (*41*). |

*Note: — = not applicable.*

*U-Turn Design*

The use of U-turn (crossover) intersections is ubiquitous across U-turn-based designs. Michigan has identified 660 feet +/- 100 feet as the optimal distance from the main intersection to the U-turn intersection on the basis of signal coordination, while North Carolina specifies 800–1,000 feet as the range of acceptable distances between the main intersection and the U-turn intersections (*40*) and Mississippi extends to 1,320 feet (*41*). A capacity analysis and anticipated storage weaving movements should be considered when determining the final location of the U-turn intersection (*33*). Safety research for MoDOT recommended that U-turn locations be located 1,000 to 2,000 feet from the intersection for low-volume combinations and 2,000 feet for medium- to high-volume combinations. Research previously conducted in Texas suggested that the spacing between the main intersection and the U-turn intersection be the maximum of the through-movement queue, left-turn queue, and U-turn queue (*36*). Table 49 is adapted from a report to the Mississippi Department of Transportation (MDOT) and contains minimum and maximum spacing of crossovers relative to the main intersection for several agencies. Ultimately, the table illustrates that the U-turn-based designs can be adapted to provide context-sensitive solutions to meet the needs of the specific site.

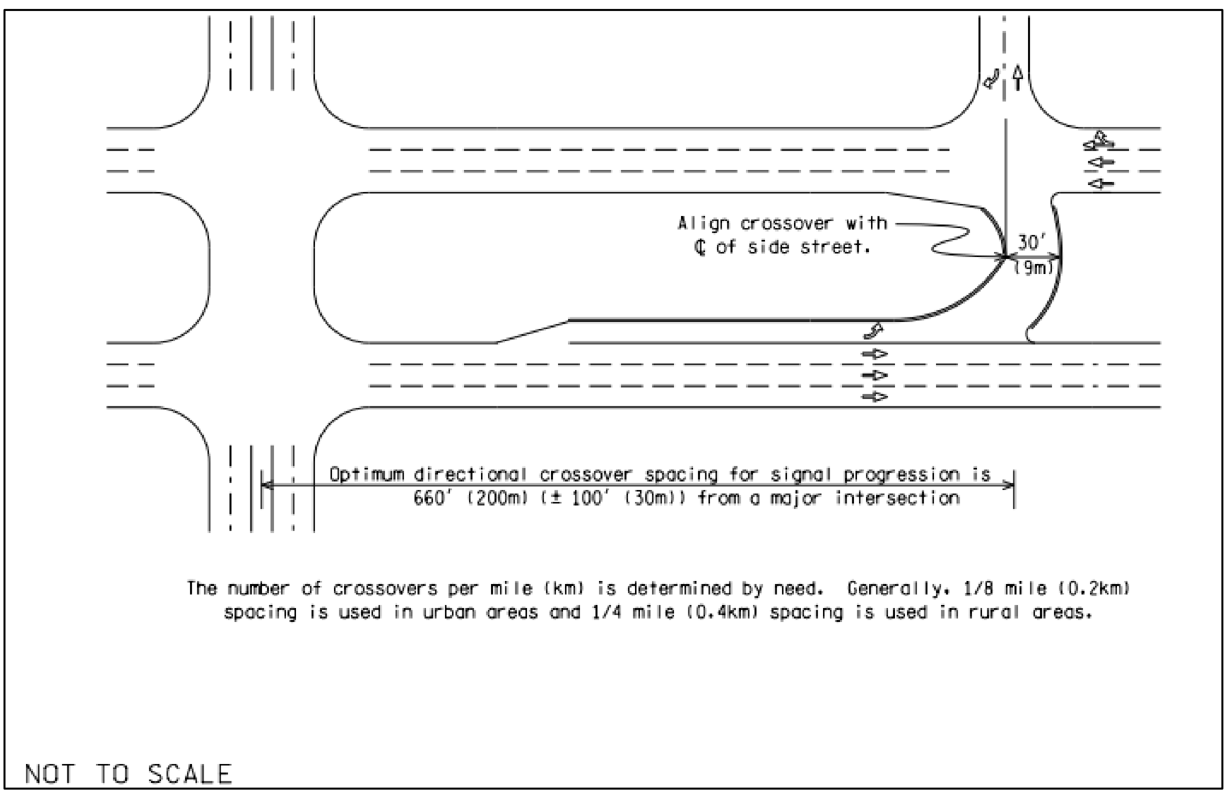
**Table 49. MUT Crossover Spacing Requirements by Agency (*41*)**

| Source | Minimum (ft) | Maximum (ft) |
|---|---|---|
| American Association of State Highway and Transportation Officials (AASHTO)[a] | 400 | 600 |
| Transportation Research Board (TRB) *Access Management Manual* | 660 | 1,320 |
| North Carolina | 800 | 1,000 |
| Michigan | 560 | 760 |
| Oregon | 990 | 1,320 |
| Missouri[b] | 600 | 1,000 |
| Mississippi | 800 | 1,320 |

*Note: [a]Based on signalized intersection treatment. [b]Specific location to be determined via capacity analysis.*

Source: Synthesis of J-Turn Design Standards and Criteria, Table 4, Page 13.

Figure 113 illustrates the recommended spacing and alignment of the U-turn intersections at MUT locations in Michigan (*43*). The figure also illustrates the recommended alignment of the median U-turn in consideration of side streets.




Source: Geometric Design Guide for Crossovers, General Placement of Crossovers, Sheet 1 of 5.

**Figure 113. General Placement of Directional Crossovers (*43*).**

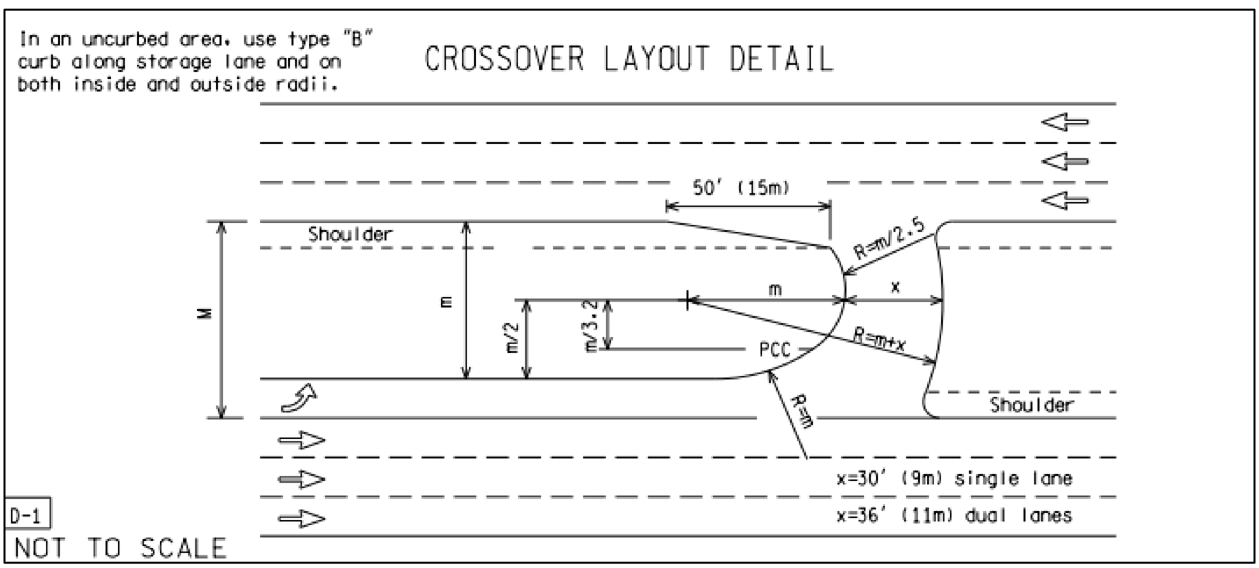
Auxiliary taper lengths are shown in Table 50 and are based on the posted speed limit and number of turning lanes.

**Table 50. Auxiliary Lane Taper Table (*43*).**

| Condition | Auxiliary Taper (ft) |
|---|---|
| Posted Speed ≤ 35 MPH | 75 |
| Posted Speed = 40 MPH | 100 |
| 45 MPH | 130 |
| 50 MPH | 180 |
| 55 MPH | 225 |
| Dual Turn Lanes | 225 |

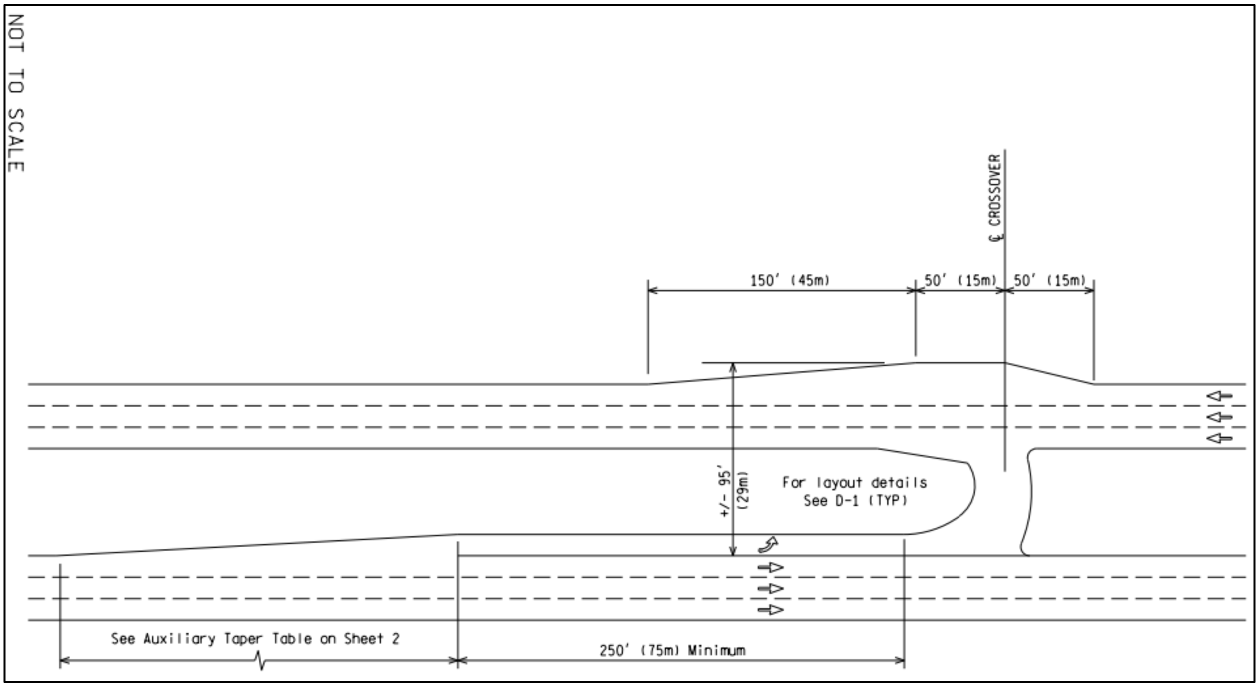
Adapted From: Geometric Design Guide for Crossovers, Auxiliary Lane Taper Table and Dual Turns, Sheets 2, 3 of 5.

Typical crossover layout design in Michigan is presented in Figure 114, which describes the inner and outer radius of the crossover as a function of the median width and number of lanes. Considerations for truck loon guidance and minimum auxiliary lane length in Michigan is shown in Figure 115, while similar information from North Carolina is shown in Figure 116. Finally, minimum designs for U-turns based on maneuver and design vehicle are shown in Figure 117.



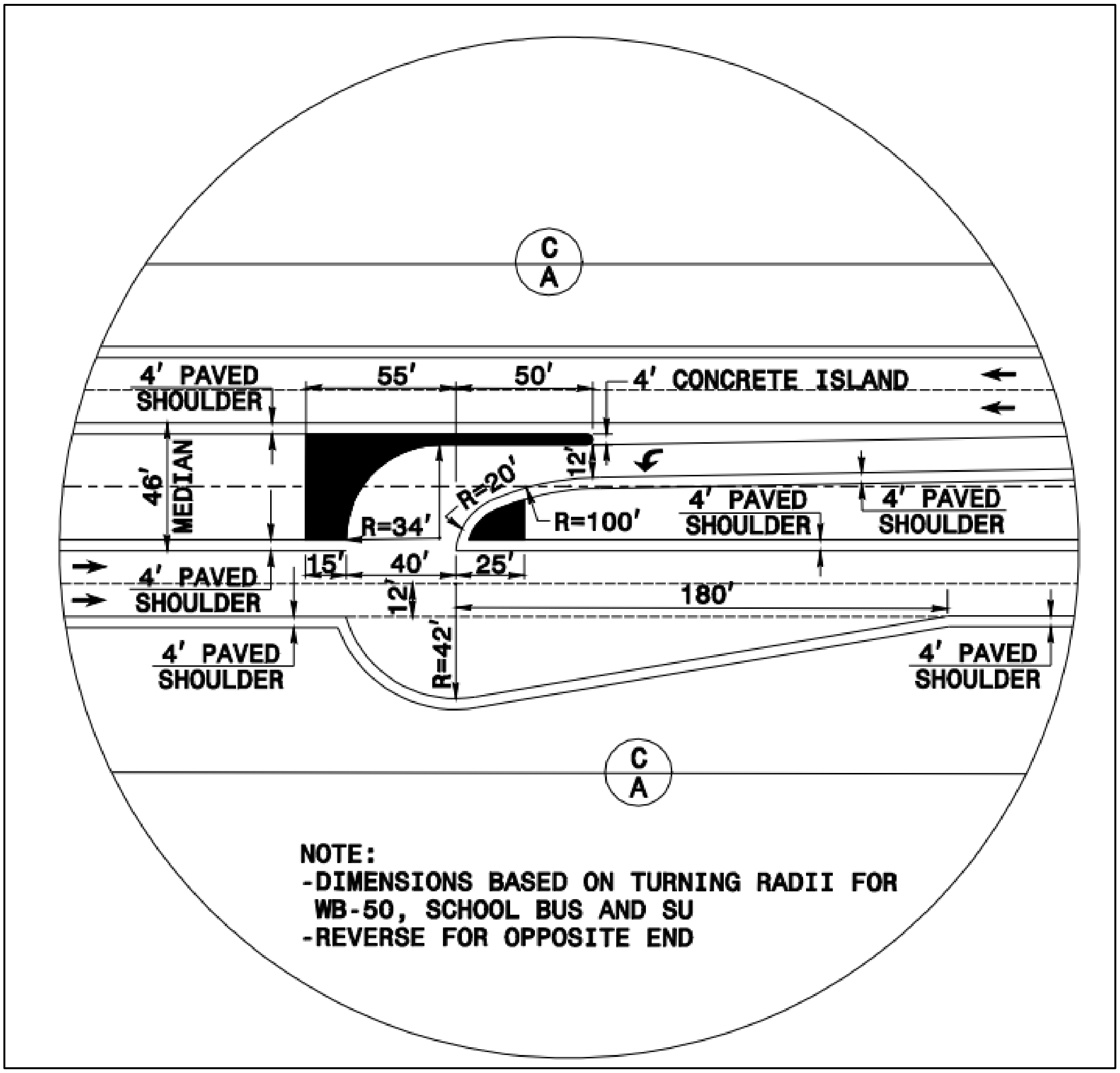

Source: Geometric Design Guide for Crossovers, Crossover Layout Detail, Sheet 2 of 5.

**Figure 114. Crossover Layout Detail (*43*).**



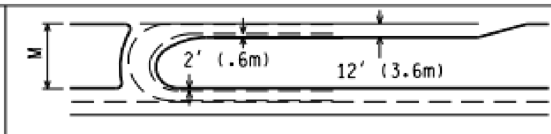
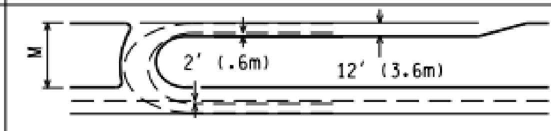
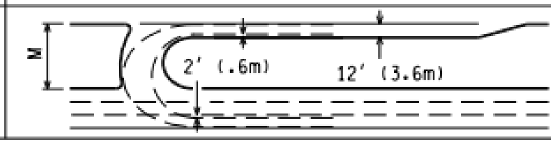

Source: Geometric Design Guide for Crossovers, Truck Loon, Sheet 4 of 5.

**Figure 115. Truck Loon Layout in Michigan (*43*).**




Source: NCDOT *Roadway Design Manual* Chapter 9, Inset "A", Page 40.

**Figure 116. North Carolina U-Turn Design (*40*).**

| Type of Maneuver | | M = Min. width of median - ft (m) for design vehicle | | | | |
|---|---|---|---|---|---|---|
| | | P | SU | BUS | WB-50 | WB-65 |
| Left Lane to Inner Lane |   | 44' (13.4m) | 76' (23.2m) | 80' (24m) | 82' (25m) | 82' (25m) * |
| Left Lane to 2nd Lane |   | 32' (9.8m) | 64' (19.5m) | 68' (20.7m) | 70' (21m) | 70' (21m) * |
| Left Lane to 3rd Lane |   | 22' (6.7m) | 54' (16.5m) | 58' (17.7m) | 60' (18m) | 60' (18m) * |

* To accommodate WB-65 semi-trucks, provide 36' (11m) crossover width or 4' (1.2m) paved area behind curb on the inside radius, from spring point to spring point.

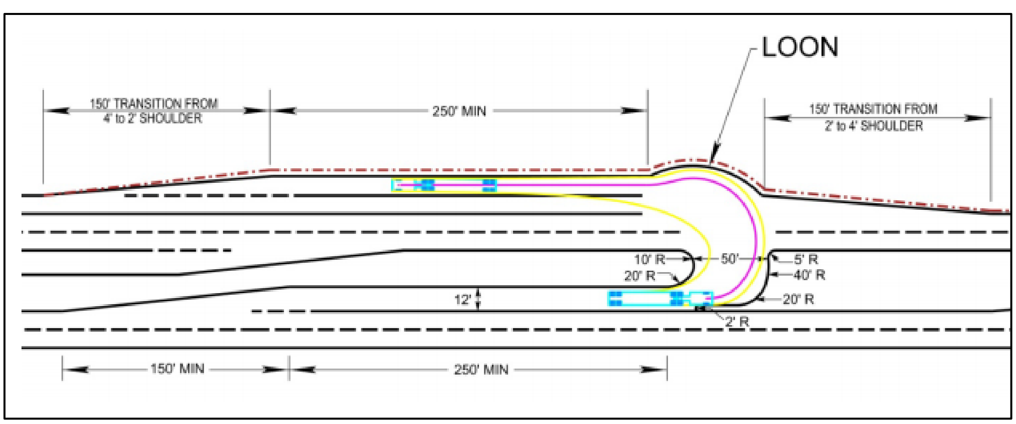
**Vehicle Codes and Length of Design Vehicle - ft (m)**

P = Passenger, 19' (5.8m)
SU = Single Unit Truck, 30' (9m)
BUS = Bus, 40' (12m)
WB-50 = Semi-Truck Medium Size, 55' (16.5m)
WB-65 = Semi-Truck Large Size, 70' (21m)

Source: Geometric Design Guide for Crossovers, Minimum Designs for U-Turns, Sheet 5 of 5.

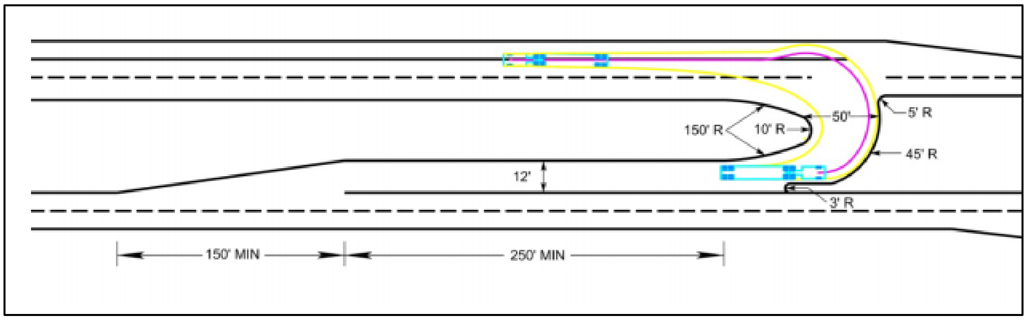
**Figure 117. Minimum Designs for U-Turns (*43*).**

A synthesis of best practices for MDOT (*41*) identified several U-turn configurations for specific median widths, shown in Figure 118 through Figure 121. In areas where larger median widths are available, acceleration lanes can be provided to aid turning vehicles in entering the traffic flow. Research has demonstrated that most vehicles merge into through traffic within the first 400 feet of an acceleration lane at these types of intersections (*44*). Additionally, the radii used in the U-turn can be varied to facilitate a more gradual turn.



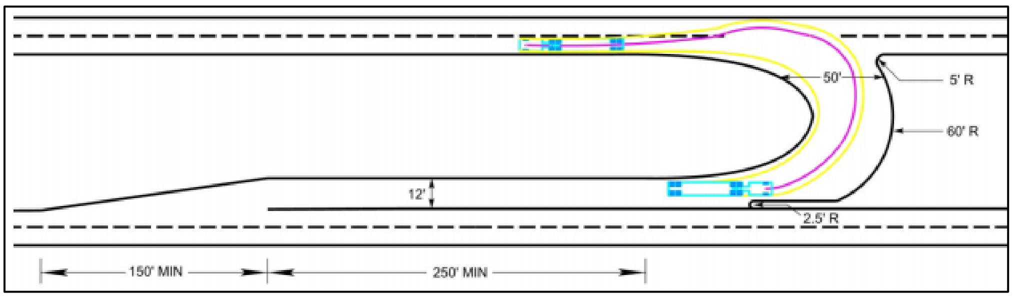

Source: Synthesis of J-Turn Design Standards and Criteria, Figure 11, Page 11.

**Figure 118. Recommended MUT Crossover Design Detail for 40-ft Medians (*41*).**



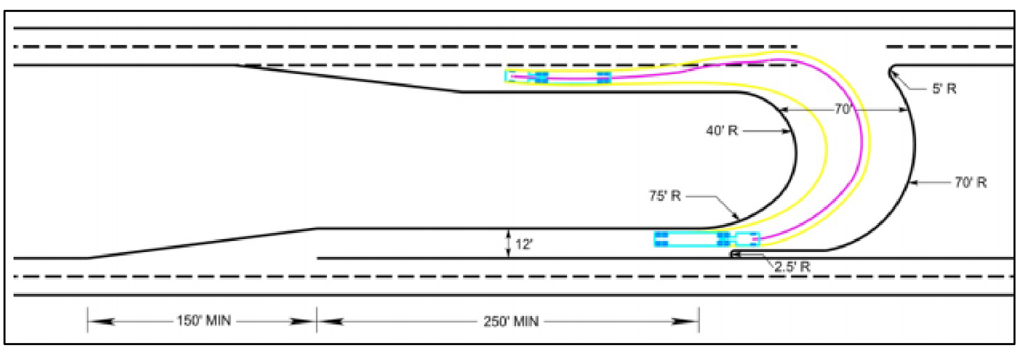

Source: Synthesis of J-Turn Design Standards and Criteria, Figure 12, Page 11.

**Figure 119. Recommended MUT Crossover Design Detail for 64-ft Medians (*41*).**




Source: Synthesis of J-Turn Design Standards and Criteria, Figure 13, Page 12.

**Figure 120. Recommended MUT Crossover Design Detail for 101-ft Medians (*41*).**

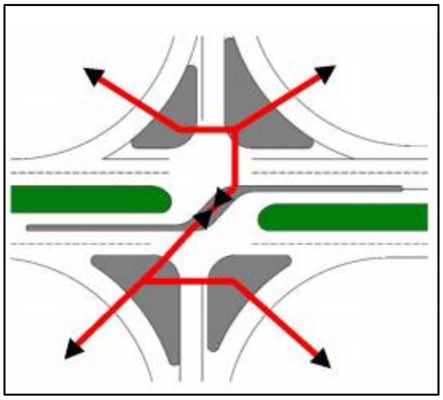



Source: Synthesis of J-Turn Design Standards and Criteria, Figure 14, Page 12.

**Figure 121. Recommended MUT Crossover Design Detail for 126-ft Medians (*41*).**

*Pedestrian Considerations*

At RCUT intersections, pedestrian-vehicle crossings can be greatly reduced by using a z-shaped crossing (*41, 37*). Figure 122 illustrates the z-crossing path.



Source: Synthesis of J-Turn Design Standards and Criteria, Figure 20, Page 19.
**Figure 122. Pedestrian Z-Crossing Path (*41*).**

*Bicycle Considerations*

The MUT design can be challenging for bicyclists for numerous reasons. Bike lanes may be located between travel lanes, lane additions, or lane merges; trucks navigating the U-turns may overtrack into the bike lane. Issues can arise when cyclists try to use the left-turn lanes on the main road, as well as the U-turns (*45*). Bicycle lanes are typically located on the outside of the traveled way, and consequently, cyclists must cut across multiple lanes of through traffic to reach the turn lanes. Cyclists can potentially avoid using the U-turn if bicycle treatments, such as a two-stage left turn, are used at the intersection. The FHWA has indicated that the desired path of cyclists follows the z-crossing used by pedestrians, with cyclists using the U-turns as an undesirable option (*42*).

*Corridor Treatment*

Many states provide some level of guidance for the use of median openings as a corridor treatment rather than to facilitate movement at a specific intersection. These openings are typically used to provide access to residences or businesses on the opposing side of the freeway relative to a vehicle. Table 51, taken from NCHRP Report 524, provides a snapshot of those policies (*46*).

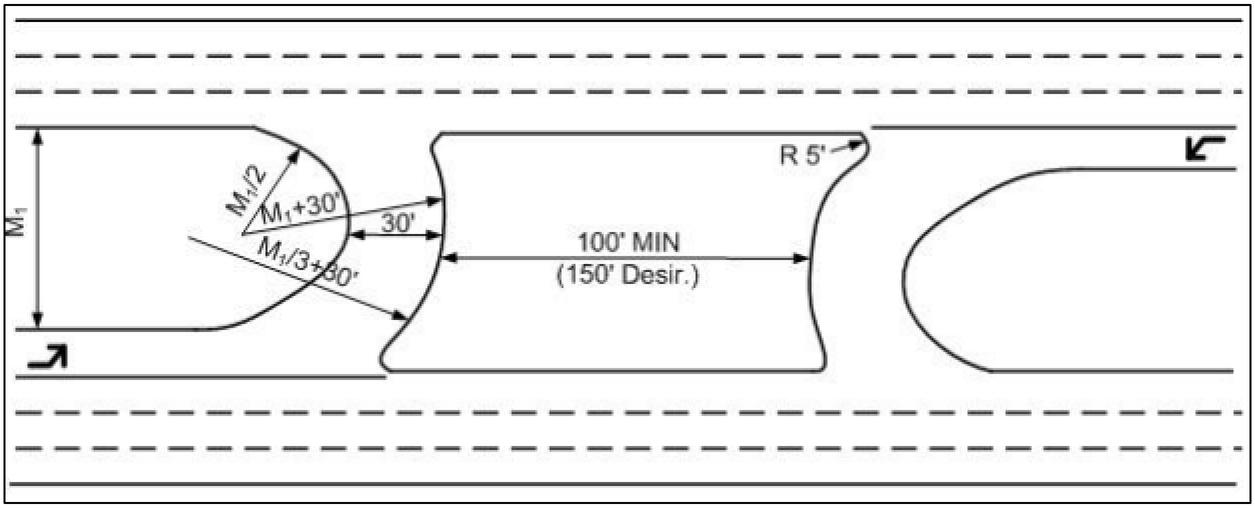
**Table 51. State Policies on Minimum Spacing Between Median Openings (*46*).**

| State | Rural Minimum spacing (ft) | Urban Minimum spacing (ft) | Comments |
|---|---|---|---|
| Alabama | 600 | 300 | — |
| Arizona | 1,320 | 660 | For businesses generating high traffic volumes the minimum spacing is 330 ft |
| California | 1,640 | 1,640 | Unsure of possible differences between rural and urban criteria |
| Florida | 1,320<br>2,640 | 330–660<br>660–1,320 | Directional<br>Conventional |
| Georgia | 1,320 | 660 | Maximum spacing 5,200 ft in rural areas and 1,320 ft in urban areas |
| Iowa | 1,000 | 660 | — |
| Idaho | 1,312 | 660 | — |
| Illinois | 2,625 (minimum)<br>5,250 (desirable) | 1,312 | Longer minimum spacing used if needed to accommodate left turn lanes |
| Louisiana | 1,500 | 500 | — |
| Maine | — | 1,312–1,640 (minor arterial)<br>1,640–1,968 (major arterial) | Criteria apply to signalized median openings only |
| Michigan | 1,320 | 660 | Desirable spacing |
| Mississippi | 1,760 | 880 | — |
| North Carolina | 1,500 | 700 (< 45 mph)<br>1,000 (45–55 mph) | Urban spacing criteria vary with operating speed |
| Nebraska | 1,000 (minimum)<br>2,000 (desirable) | 600 | — |
| New Mexico | 600 | 300 | — |
| Nevada | 660 | — | In urban areas, have criteria for access spacing rather than median opening spacing |
| Ohio | — | — | Have spacing criteria for driveways but not for median openings |
| Oklahoma | 2,640 (minimum)<br>5,280 (desirable) | 1,320 | Longer spacing used in rural areas if needed to accommodate left turn lanes |
| Pennsylvania | 1,500 | 1,500 | — |
| South Carolina | 1,000 | 500 | — |
| Texas | 1,320–2,640 | 1,320–2,640 | — |
| Virginia | 700–1,000 (35–45 mph)<br>500–650 (50–70 mph) | 700–1,000 (35–45 mph)<br>500–650 (50–70 mph) | Urban spacing criteria vary with design speed |
| Range | 500–2,640 | 300–2,640 | — |
| Average | 1,400 | 880 | — |

*Note: — = Not applicable.*

Source: NCHRP Report 524, Table 11, Page 29.

Another spacing consideration for the use of median U-turns as a corridor treatment is the proximity of U-turns facilitating crossing over in opposite directions. Figure 123 shows the minimum and desirable spacing of these types of movements.




Source: Development of Performance Matrices for Evaluating Innovative Intersections and Interchanges, Figure 14, Page 22.

**Figure 123. Directional Crossover Design on Highway with Curbs (*47*).**

### Crossover-Based Intersections

Crossover-based intersections are designed to facilitate left-turn movements without the use of U-turns. The crossover intersections used in these types of designs move either mainline through movements or mainline left turns to the opposing side of the roadway. Queue spillback from the main intersection to the crossover intersections is a critical consideration when designing these types of intersections, and research has indicated that the ratio of queue size to storage bay length is a key consideration of these designs (*48*, *49*)

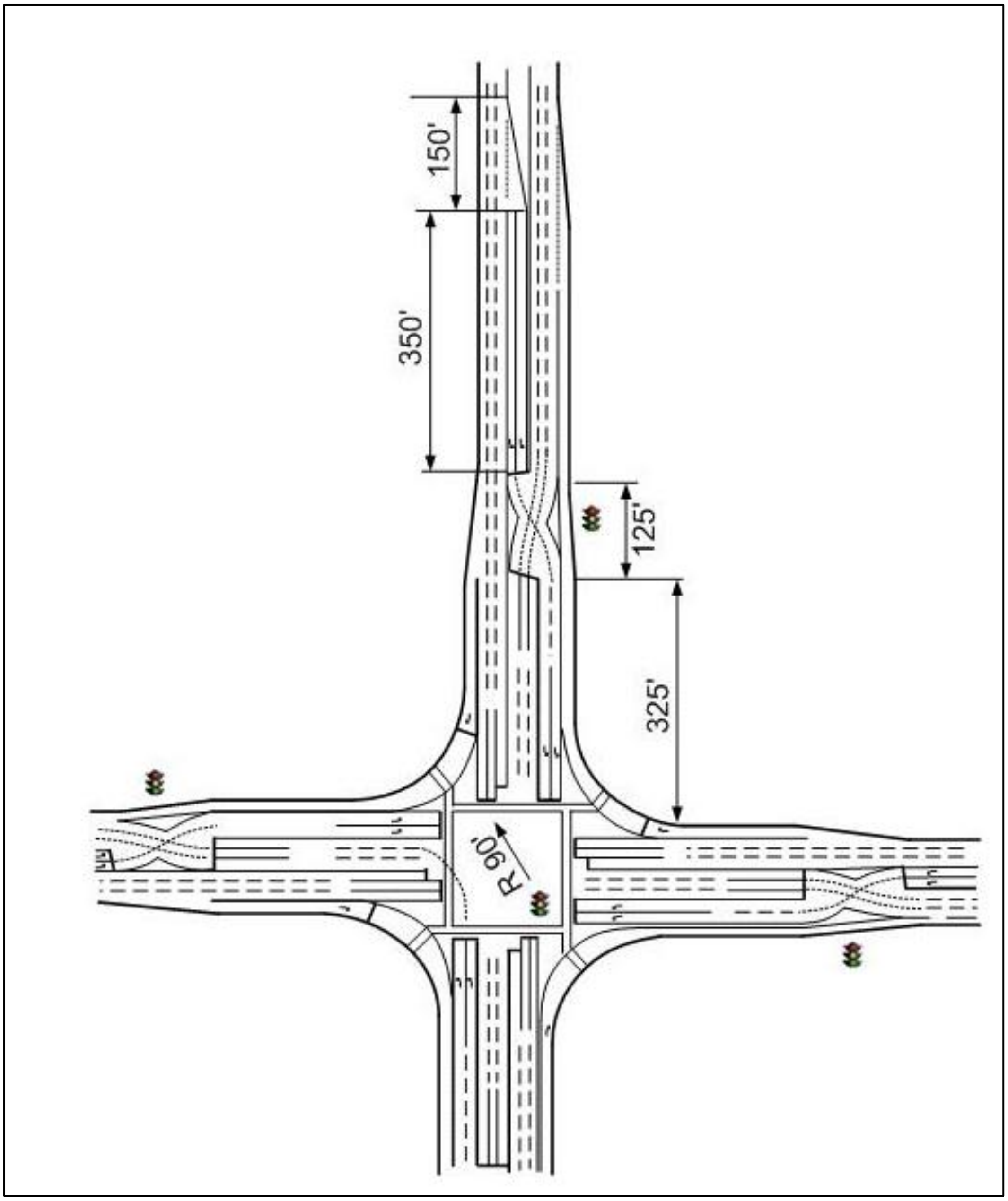
#### *Displaced Left Turns*

DLTs should be considered at intersections with the following characteristics:

- Moderate to heavy traffic volumes in all directions (*3, 34*, *38*).
- Opposing legs have similar through volumes (*3*).
- Heavy left-turn traffic volumes (*3*).
- A limited number of driveways or access points near the intersection (*3*).
- High-volume major and minor approaches in unbalanced traffic (*38*).
- High volumes with little demand for U-turns (*36*).
- Heavy congestion that causes many signal phase failures or left-turn queues to spill beyond storage bays (*36*).
- Some right-of-way is available along the arterial near the intersection (*36*).

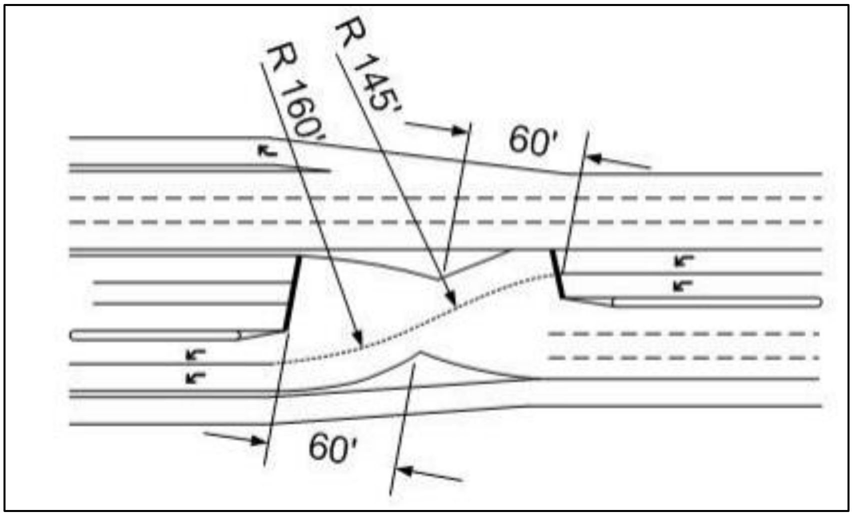
- Access to the arterial from the parcels located within the intersection influence area can be controlled (*36*).

The intersection allowing left-turning vehicles to cross oncoming traffic is the critical element of this design. This crossover intersection is typically located 300–400 feet upstream of the main intersection (*36*, *50*). The intersection angle should be between 10 and 15 degrees dependent on median width and mainline alignment (*36*). The angle should be designed to be as great a help as possible to reduce possibility of wrong-way entry (*47, 51*). An image of a DLT with typical dimensions is shown in Figure 124. A close-up image of the crossover intersection is provided in Figure 125. The latter figure illustrates typical radii values at the crossover intersection, which typically range between 100 and 200 feet (*47*).




Source: Development of Performance Matrices for Evaluating Innovative Intersections and Interchanges, Figure 11, Page 18.

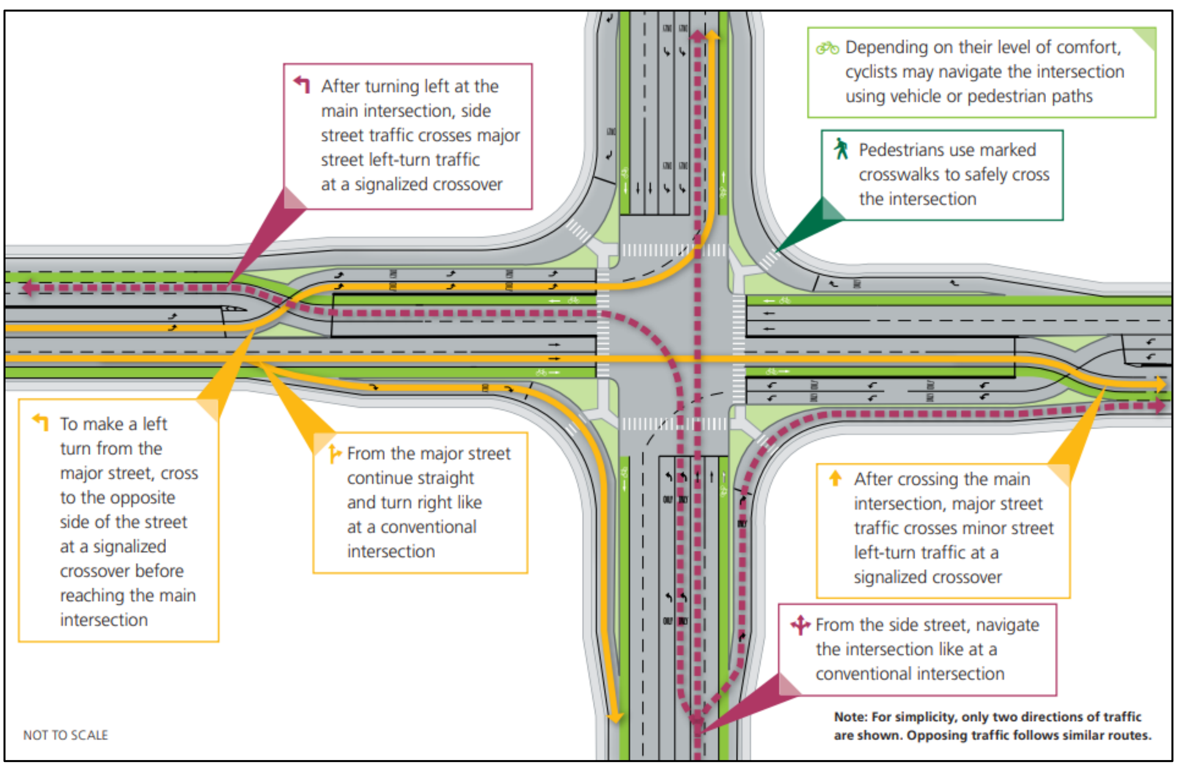
**Figure 124. Typical Four-Approach DLT (*47*).**




Source: Development of Performance Matrices for Evaluating Innovative Intersections and Interchanges, Figure 12, Page 19.

**Figure 125. Crossover Design Details (*47*).**

Pedestrians navigate DLTs in crosswalks similar to conventional intersections (*3*). The use of right-turn bypass lanes at these intersections may result in the need for signage to communicate appropriate behavior. Figure 126 shows how various road users navigate DLTs. This particular image uses the right-turn bypass lanes as previously mentioned.




Source: VDOT Innovative Intersections and Interchanges, How to Navigate, Displaced Left Turn.

**Figure 126. Navigating a DLT (*3*).**

*Diverging Diamond Interchanges*

DDIs should be considered at locations that possess the following characteristics:

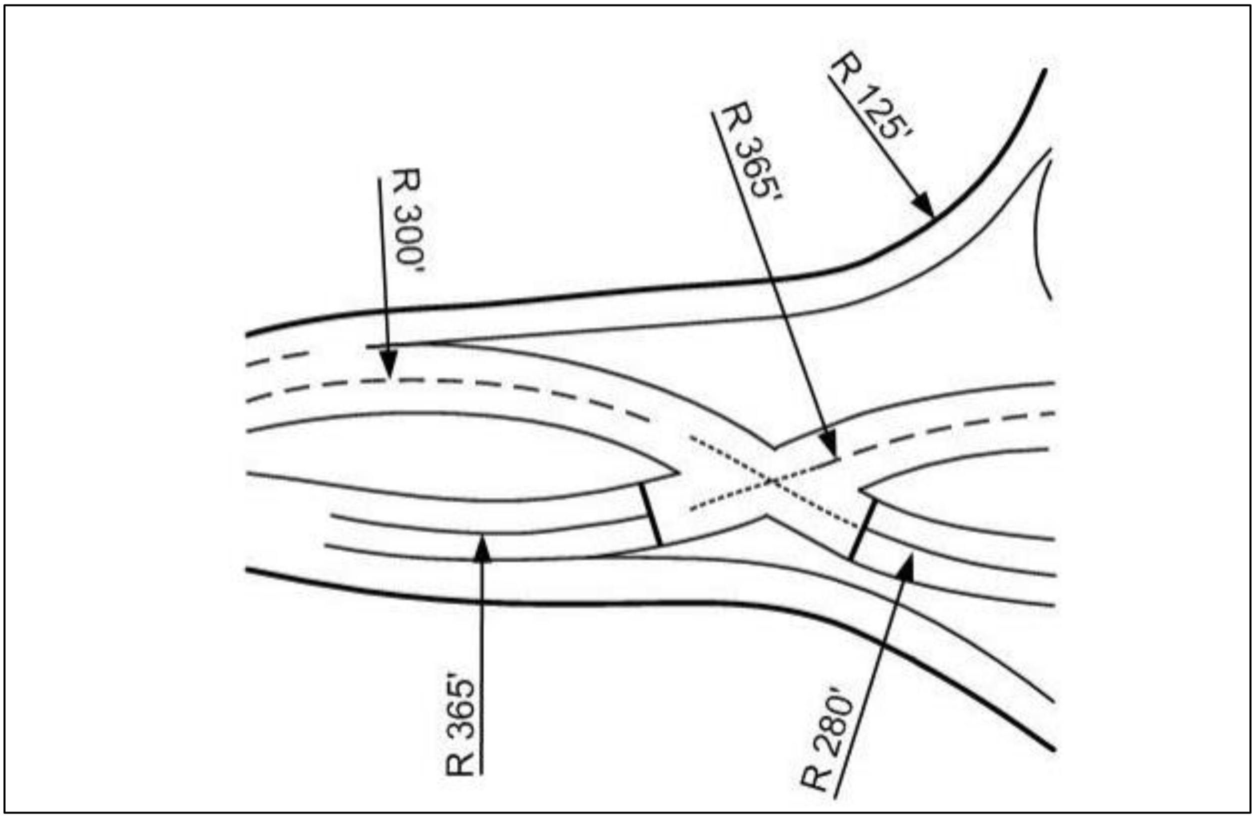
- Heavy left-turn traffic volumes onto and off the freeway ramps (3, 37).
- Unbalanced volumes (*37*).
- No adjacent traffic signals or nearby driveways (*3*).
- Limited roadway width for left-turn lanes between ramp intersections and limited right-of-way to expand (*3*).

Two major design considerations exist for these designs: the spacing between the DCIs and the angle of the DCIs. A review of best practices in Utah indicates that 800 to 1,000 feet is adequate spacing between the DCIs (*52*). The approach angle leading into the DCI should be 30 degrees (*47*, *52*). The angle of the intersection of the two directions of travel should be as close to 90 degrees as possible. Other states have indicated that greater intersection angles will allow the DCIs to feel more like traditional intersections while narrower angles increase the likelihood of wrong-way movements. Sharply angled curbs (as opposed to rounded ones) should be used to further discourage wrong-way drivers (*52*). Reverse curvature should be used upstream of the DDI to calm traffic and align vehicles with the DCI. Design speeds should be lower than traditional interchanges (35 mph or less) to reduce collision severity, and proximity of the DCIs to other signalized intersections can have a significant impact on the efficiency of the DDI (*6*). The design speed of the DDI should be lower than that of the approaching roadway, but speed reduction should be no greater than 15 mph with 10 mph being preferable (*47*). Additionally, the following items have been identified in research literature as being pertinent to DDI design (*47*):

- Radius design should accommodate speeds of 25 to 30 mph.
- Superelevation may not be needed as it may detract from the traffic calming effect.
- Lane width should be about 15 ft.
- Design should accommodate WB-67 trucks.
- Adequate lighting should be provided.
- Nearside signals should be considered.
- Designs are only appropriate when high turning volumes are present.
- Nearby intersection with long cycles should be avoided.

- Pedestrians at free-turning movements should be evaluated, and pedestrian signals may be needed.
- Noses of median island should be extended to prevent erroneous maneuvers.
- Left- and right-turn bays should be designed to allow separate signal phases.
- Design should be as flat as possible due to the critical nature of sight distance at unfamiliar roadway designs.

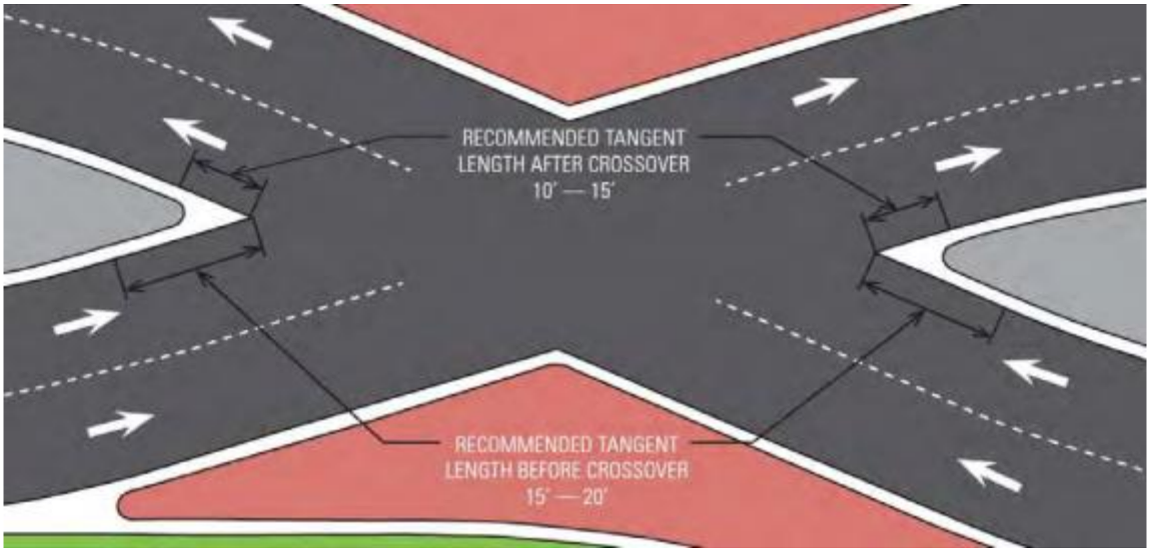
The totality of these design principles results in a DCI design similar to the recommended layout in Figure 127.




Source: Development of Performance Matrices for Evaluating Innovative Intersections and Interchanges, Figure 10, Page 12.

**Figure 127. Suggested DCI Layout Based on Research from Utah (*47*).**

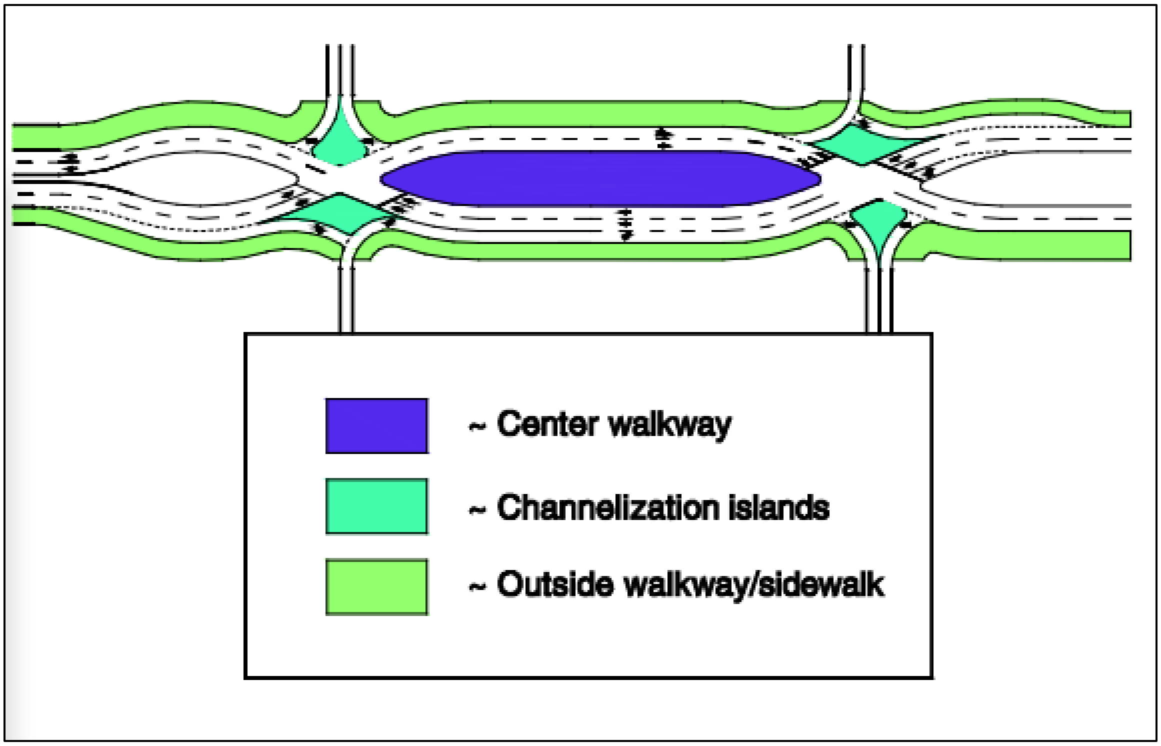
Tangent space is needed before and after the DCIs to allow vehicles to properly align themselves in the lane. Figure 128 shows recommended tangent lengths.




Source: Missouri's Experience with a Diverging Diamond Interchange, Figure 2.5, Page 8.

**Figure 128. MoDOT Recommended Tangent Length Before and After DCI (*53*).**

Pedestrian passage through a DDI can be provided as a walkway outside the traveled way or as a center walkway in the median (*6, 7, 53*), as illustrated in Figure 129. Bicycles should operate through DDIs in a manner consistent with local cycling policies. To accommodate both pedestrians and cyclists, the width of the center walkway should be a minimum of 10 ft with 14 ft preferred (*6*). Additionally, existing bike infrastructure should continue through the interchange when possible (*53*).




Source: Diverging Diamond Interchange Informational Guide, Exhibit 3-1, Page 30.

**Figure 129. Schematic of DDI Right-Of-Way Availability for Multimodal Facilities (*7*).**

**Other Intersection/Interchange Types**

*Single-Point Urban Interchange (SPUI)*

SPUIs should be considered at interchange locations with:

- Limited right of way (*3*).
- Heavy left-turn volumes onto and off the interstate or primary road ramps (*3*).
- Space to accommodate wider intersection and structure widths (*3*).
- Traffic between 20,000 and 35,000 AADT on the major roadway and from 15,000 to 30,000 AADT on the minor roadway (*33*).

There are several disadvantages to the SPUI design that must be thoughtfully considered when a SPUI is a feasible alternative. First, the construction costs of bridges are relatively high (*33*). The typical bridge span, which usually carries the major roadway, is 120 to 200 (*54*) or even 220 feet (*33*). The intersections are difficult to expand in the future, require complex staging to retrofit, require longer structure spans with higher profiles and deeper structure depths, and increase pedestrian and cyclist circulation time (*55*).

**Table 52. Minimum Radii and Superelevation for Turning Speeds (*33*).**

| Operating Speed (mph) | Radius (ft) | Superelevation (ft/ft) | Length of Circular Arc, Desirable (ft) |
|---|---|---|---|
| 15 | 50 | 0.00 | 60 |
| 20 | 90 | 0.02 | 60 |
| 25 | 150 | 0.04 | 70 |
| 30 | 230 | 0.06 | 110 |
| 35 | 310 | 0.08 | 140 |
| 40 | 430 | 0.08 | 190 |
| 45 | 540 | 0.08 | 200 |

Source: MoDOT Engineering Policy Guide, Table 2, Section 234.4.1.9.

Pedestrians only cross a portion of the intersection during a single cycle, and exit ramp volumes may necessitate added traffic signals or pedestrian hybrid beacons (*55*). Pedestrian crossings at the local road within the SPUI should be avoided.

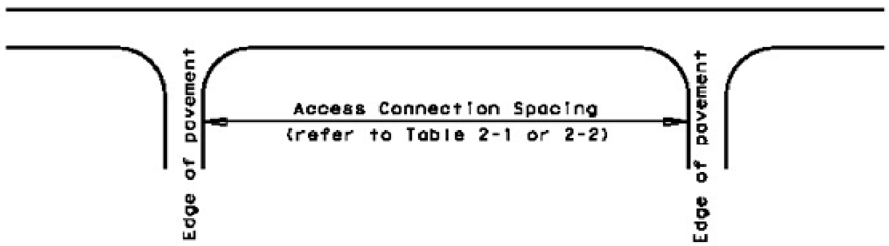
The required green and all-red clearance intervals necessary for a bicycle to clear most SPUI intersections are substantially longer than what is needed for a motor vehicle (*55*). Consequently, locations near schools, transit centers, and other bicycle destinations may make SPUIs less desirable.

## ACCESS

Access management is important in the vicinity of any intersection so that it can be best suited to meet the needs of those who use it. While rural intersections may have fewer demands than their urban counterparts, access needs must still be considered, particularly at high speeds, as the intersection's influence area increases. This section contains guidance on access related to specific intersection types.

### Conventional Intersection Access Guidance

The TxDOT *Access Management Manual* (AMM) (*56*) provides guidance on access for conventional intersections. In Chapter 2, Section 3 of the TxDOT AMM, it states that access connection distances are based on stopping sight distance and are intended for passenger cars on a level grade. These distances may be increased for downgrades, truck traffic, or where otherwise indicated for the specific circumstances of the site and the roadway. The distance between access connections is measured along the edge of the traveled way from the closest edge of pavement of the first access connection to the closest edge of pavement of the second access connection, as shown in Figure 130.




Source: TxDOT AMM, Figure 2-1

**Figure 130. Access Connection Spacing Diagram (*56*).**

Where topography or other existing conditions make it inappropriate or not feasible to conform to the connection spacing intervals, the location of reasonable access will be determined with consideration given to topography, established property ownerships, unique physical limitations, and/or physical design constraints. The selected location should serve as many properties and interests as possible to reduce the need for additional direct access to the highway. In selecting locations for full movement intersections, preference will be given to public roadways that are on local thoroughfare plans.

In the absence of any safety or operational problems, additional access connections may be considered. Any additional access must not interfere with the location, planning, and operation of the public street system. Where the property abuts or has primary access to a lesser function road, to an internal street system, or by means of dedicated access easement, any access to the state highway will be considered as an additional access.

*New Highways on New Alignments (New Location)*

Guidance from Chapter 2, Section 3 of the TxDOT AMM (*56*) states that when a new access-controlled highway is constructed on a new alignment (new location), direct access to the new highway will be determined prior to right-of-way acquisition and will be described in the right-of-way deeds.

Such new highways may initially have at-grade intersections, though they may be intended for ultimate upgrade to full freeway criteria. In such cases, temporary access may be permitted where a property would otherwise be landlocked. When temporary access is permitted, the access permit will clearly state that the connection is temporary and will identify the terms and conditions of its temporary use and the conditions of the permanent access connection. The permit will also clearly state that the temporary connection will be closed and removed at such time that permanent access becomes available.

*Other State System Highways*

For state highway system routes that are not new highways on new alignments, freeway mainlanes, or frontage roads, Table 2-2 in the TxDOT AMM (reproduced here as Table 53) provides minimum connection spacing criteria. The TxDOT AMM also describes a variance process for modifications to those criteria.

**Table 53. State Highways Connection Spacing Criteria (*56*).**

| Minimum Connection Spacing [1 2 3] | |
|---|---|
| **Posted Speed (mph)** | **Distance (ft)** |
| $\leq$ 30 | 200 |
| 35 | 250 |
| 40 | 305 |
| 45 | 360 |
| $\geq$ 50 | 425 |

NOTES:
1. Distances are for passenger cars on level grade. These distances may be adjusted for downgrades and/or significant truck traffic. Where present or projected traffic operations indicate specific needs, consideration may be given to intersection sight distance and operational gap acceptance measurement adjustments.
2. When these values are not attainable, refer to the variance process as described in Chapter 2, Section 5.
3. Access spacing values shown in this table do not apply to rural highways outside of metropolitan planning organization boundaries where there is little, if any, potential for development with current ADT levels below 2000. Access connection spacing below the values shown in this table may be approved based on safety and operational considerations as determined by TxDOT.

Source: TxDOT AMM, Table 2-2

Note that Table 53 does not apply to many rural highways (e.g., outside of metropolitan planning organization boundaries, little potential for development, current average daily traffic [ADT] volumes below 2,000). For those highways, access location and design are evaluated based on safety and traffic operation considerations. Such considerations may include traffic volumes, posted speed, turning volumes, presence or absence of shoulders, and roadway geometrics. One example of an application of considering site-specific conditions is the Odessa District Access Management Policy Supplement (*57*) that emphasizes access guidelines for energy highways, which typically have high speeds and large volumes of heavy vehicles. The requirements described in the current version of the supplement are shown in Table 54 and have potential applicability on other rural state highways with high speeds, high volumes, and high turning demand.

**Table 54. Access Management Design Requirements in Odessa District Access Management Policy Supplement (*57*).**

| Classification[1] | Passing Lanes | Turn Lanes | Access Point Spacing (Passenger Cars) | Access Point Spacing (Increased for Heavy Trucks) | Minimum Offset Between Access on Opposite Sides of Road | Hybrid Driveway Design[2] |
|---|---|---|---|---|---|---|
| Energy Highway—Primary Route | YES | YES | Minimum 1/2 Mile | Minimum 1 Mile | 1/4 mile | YES |
| Energy Highway—Secondary Route | OK | YES | Minimum 1/3 Mile | Minimum 3/4 Mile | 1/8 mile | YES |
| Energy Highway—Minor Route | NO | OK | Table 2-2 [3] | Table 2-2 | Minimize where possible | Preferred |

- Passing Lanes—Include in design of roadway widening/repaving projects.
- Left-Turn Lanes—Include key left-turn locations in design (high volume, restricted sight); partner with applicant for locations not under design.
- Right-Turn Lanes—Add shoulders to roadways identified for turn lanes; applicants to add shoulders for acceleration and deceleration purposes at driveways if not present.
- Access Point Spacing—The separation of the driveways or access points will be governed by the highest demand. Two locations with primarily passenger car traffic (man-camps) would need to be separated by the passenger car distance. A location with primarily passenger car traffic adjacent to a primarily truck traffic location would be governed by the truck traffic.
- Driveway Consolidation—Adding new driveways may require consolidating locations to minimize the number of access points.
- Driveway Signing—New driveways shall be marked with a D3-1 Sign (green background, white 8-inch letters) mounted on a 7-ft pole near the edge of right-of-way. The text of the street sign shall be the milepost marking to the first decimal place as defined by the district staff.
- Driveway Design—Hybrid configuration allows the cab to track for the smaller radius and the trailer tires will off-track on the apron preventing damage to fences, pavement edge, etc. Designs submitted in the hybrid driveway configuration are presumed to meet all engineering requirements. Alternative configurations in accordance with the TxDOT *Roadway Design Manual* will also be considered with substantiating traffic data.

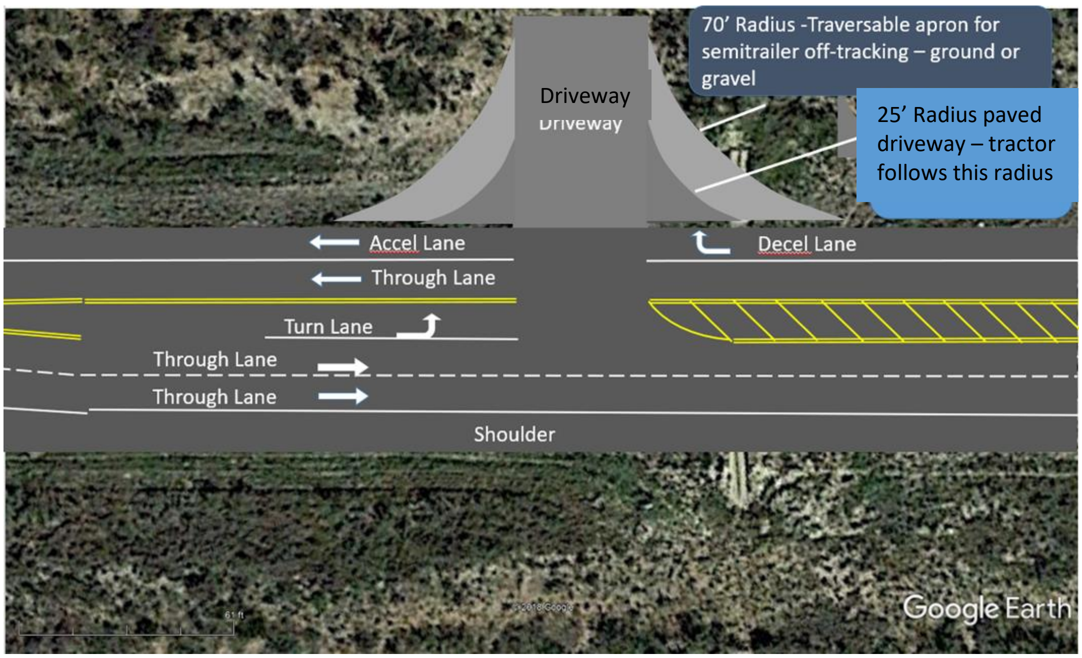
NOTES: See Table 55 for definitions of Energy Highway Classifications.
See Figure 131 for schematic of Hybrid Driveway Design.
See Table 53 for a reproduction of TxDOT *Access Management Manual* Table 2-2.

Source: Odessa District Access Management Policy Supplement, Table 1.

**Table 55. Energy Highway Definitions (*58*).**

| Classification | Functions Served by the Energy Highway | Total Traffic Ranges (Vehicles per Day) | Truck Traffic Ranges (Trucks per Day) |
|---|---|---|---|
| Energy Highway—Primary Route | Connectivity<br>Bulk Material Movement<br>Local Access | > 6,000 ADT | > 25% of all vehicles<br>OR<br>1,500 trucks per day |
| Energy Highway—Secondary Route | Bulk Material Movement<br>Local Access | 2,000 to 6,000 ADT | > 25% of all vehicles<br>OR<br>1,200 trucks per day |
| Energy Highway—Minor Route | Local Access | < 2,000 ADT | > 25% of all vehicles<br>OR<br>1,000 trucks per day |

Source: Development of Access Management Policy Guidance, Attachment 1, Exhibit F-12.




Source: Odessa District Access Management Policy Supplement, Figure 1.

**Figure 131. Hybrid Driveway Design (*57*).**

### Frontage Roads

The TxDOT AMM (*56*) discusses frontage road intersections separately from other intersections. It states that freeway frontage roads normally have at-grade interchanges with the arterial streets, which are generally perpendicular to the freeway and are grade-separated from the freeway mainlanes. Under fully developed conditions, the at-grade intersections of frontage roads and arterials are typically signalized. Table 2-1 in the AMM (reproduced here as Table 56) gives the minimum connection spacing criteria for frontage roads; however, smaller spacing may be allowed under the variance process.

**Table 56. Frontage Road Connection Spacing Criteria (*56*).**

| Minimum Connection Spacing (feet) [1 2] | | |
|---|---|---|
| **Posted Speed (mph)** | **One-Way Frontage Roads** | **Two-Way Frontage Roads** |
| ≤ 30 | 200 | 200 |
| 35 | 250 | 300 |
| 40 | 305 | 360 |
| 45 | 360 | 435 |
| ≥ 50 | 425 | 510 |

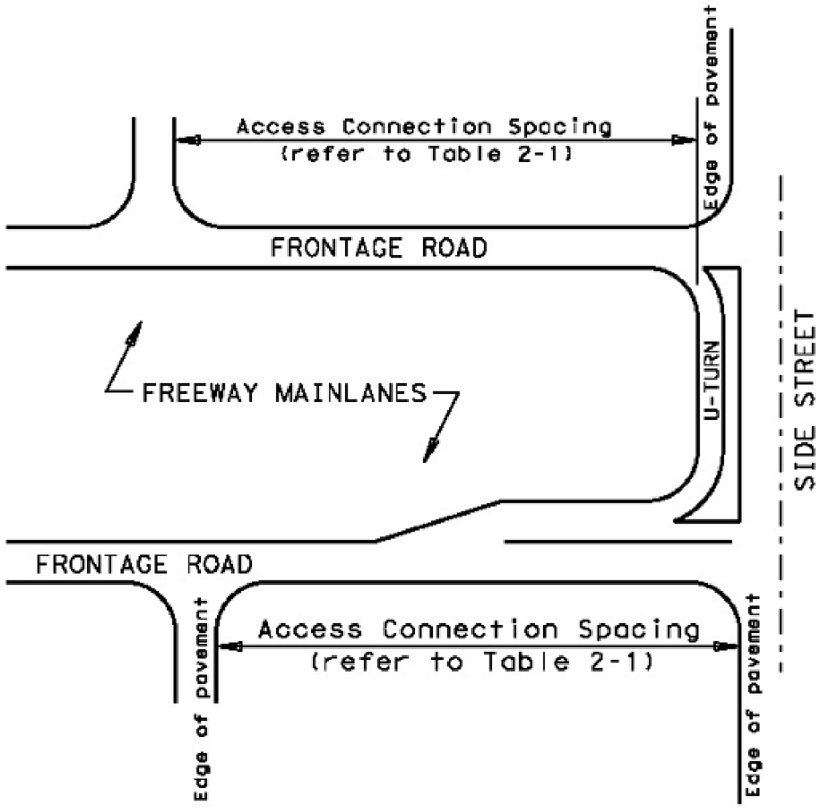
NOTES:

1. Distances are for passenger cars on level grade. These distances may be adjusted for downgrades and/or significant truck traffic. Where present or projected traffic operations indicate specific needs, consideration may be given to intersection sight distance and operational gap acceptance measurement adjustments.
2. When these values are not attainable, refer to the variance process as described in Chapter 2, Section 5.

Source: TxDOT AMM, Table 2-1.

For areas with conventional diamond ramp patterns, where an exit ramp is just upstream of the arterial street, the most critical areas for operations are between the exit ramp and the arterial street and between the arterial street and the entrance ramp. In X-ramp configurations, where the exit ramp is just downstream of the arterial street, the most critical areas are between the exit ramp and the subsequent entrance ramp. While Table 56 gives minimum connection spacing criteria, the critical areas with respect to the ramp pattern may need greater spacing requirements for operational, safety, and weaving efficiencies.

The distance between access connections is measured along the edge of the traveled way from the closest edge of pavement of the first access connection to the closest edge of pavement of the second access connection, as shown in Figure 130. Additionally, the access connection spacing in the proximity of frontage road U-turn lanes will be measured from the inside edge of the U-turn lane to the closest edge of the first access connection, shown in AMM Figure 2-3 (reproduced here as Figure 132).




Source: TxDOT AMM, Figure 2-3.

**Figure 132. Frontage Road U-Turn Spacing Diagram (*56*).**

## Roundabouts

Roundabouts can provide a useful tool within an access management program to provide U-turn opportunities at the intersections, thereby allowing for a reduction of full access points along the roadway segment. However, within the vicinity of an individual roundabout intersection, property access must also be carefully evaluated. Two general categories of access related to roundabouts are access into the roundabout itself and access near the roundabout. The FHWA's *Roundabouts: An Informational Guide* in NCHRP Report 672 (*2*) provides more detail on both categories, but a summary of information from that guide is provided here.

### *Access into the Roundabout*

It is preferable to avoid locating driveways with direct access to a roundabout; however, site constraints may mean that a direct-access driveway is necessary. The following are criteria that should be met in order to determine that providing driveway access is necessary:

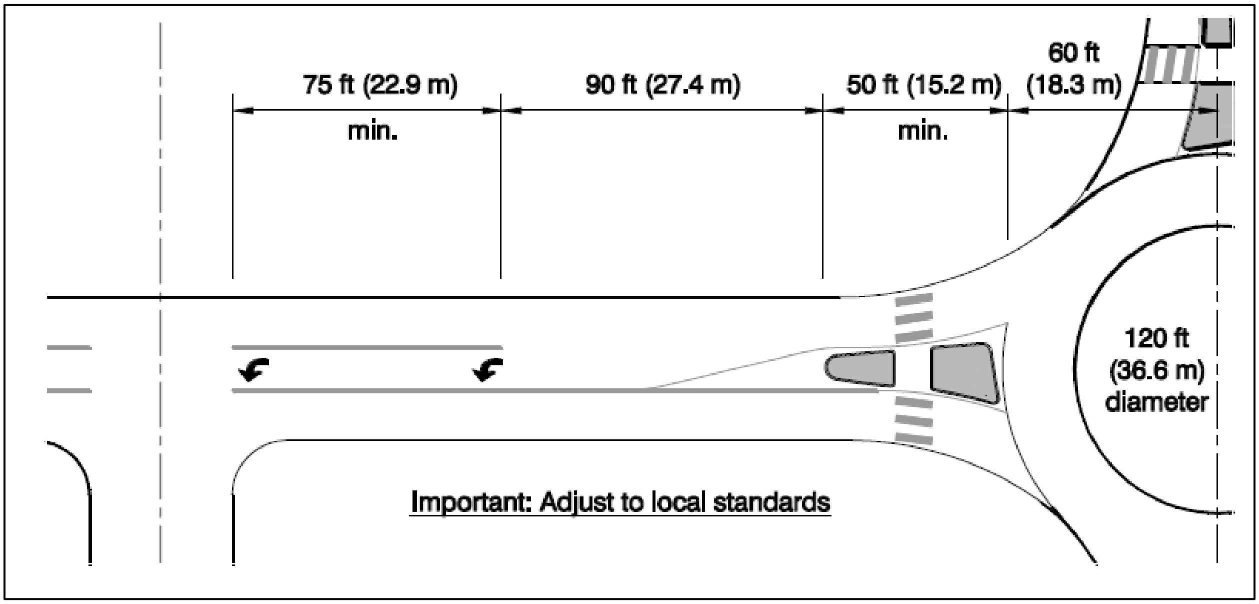
- No alternative access point is reasonable.
- Traffic volumes are sufficiently low to minimize the likelihood of errant vehicle behavior (e.g., low trip generation, predominantly familiar drivers).
- Driveway design should provide accommodation for drivers to turn around on the property without needing to back into the roundabout if a wrong turn is made.
- Driveway design should include appropriate intersection site distance from the driveway and stopping sight distance from the approach on the adjacent primary roadway.

*Access near the Roundabout*

Public and private access points near a roundabout often have restricted operations due to the channelization of the roundabout. Driveways blocked by the splitter island will be restricted to right-in/right-out operation and are best avoided unless the impact is expected to be minimal and/or no reasonable alternatives are available. Driveways between the crosswalk and yield line should be avoided to minimize conflicts and confusion for both pedestrians and drivers.

The ability to provide an access point that allows all movements (i.e., full access) is governed by a number of factors:

- *Capacity of the minor movements at the access point.* A standard unsignalized intersection capacity analysis should be performed to assess the operational effectiveness of an access point with full access.
- *Left-turn storage on the major street to serve the access point.* For all but low-volume driveways, it is often desirable to provide separate left-turn storage for access points downstream of a roundabout to minimize the likelihood that a left-turning vehicle will block the major street traffic flow.
- *Available space between the access point and the roundabout.* A minimum distance is required to provide adequate roundabout splitter island design and left-turn pocket channelization. Figure 133 shows an example of the dimensions of a left-turn downstream of a roundabout.
- *Sight distance.* A driver at the access point should have proper intersection sight distance and should be visible when approaching or departing the roundabout, as applicable.




Source: NCHRP Report 672, Exhibit 6-91, Page 6-98.

**Figure 133. Example Dimensions for Left-Turn Access near Roundabouts (*2*).**

**U-Turn-Based Intersections**

*Access into the U-Turn-Based Intersection*

The location of unsignalized access points such as driveways and minor streets between the bounds of the U-turn intersections is relatively common practice; previously presented guidance from Michigan (*43*) describes how to design U-turn intersections to coincide with such access points. Due to the presence of the median associated with these types of facilities, all access points are right-in/right-out unless aligned with a U-turn intersection, whether for a specific intersection or a U-turn intersection deployed as a corridor treatment. If a truck loon is provided at the U-turn intersection, it is undesirable to locate a driveway or intersection on the opposite side of the arterial. Access points near the main intersection should be avoided, particularly in the presence of dedicated right-turn lanes.

*Access near the U-Turn-Based Intersection*

Right-in/right-out access points are common along divided corridors in relatively close proximity to the median U-turn intersections. In the case of signalized median U-turns, queuing on the main road may restrict the ability of vehicles to enter traffic if access points are placed too close to the signal. Furthermore, the presence of adjacent signals must be considered to ensure proper coordination along the corridor.

### Displaced Left Turns

When the DLT technique is used on all four approaches, access to properties located in the quadrants of the intersections is generally limited (*29*). Driveways near the main intersection of the DLT (within the bounds of the DCIs) have to be right-in and right-out (*47*). A DLT will have unique traffic patterns, channelizing devices, and medians that would preclude left-turning driveway movements near the intersection.

### Diverging Diamond Interchanges

All access into the DDI is controlled by the DCIs and freeway off-ramps. In order to provide safe and efficient operation of the DDI, driveway consolidation and turning movement restrictions are commonly used (*52*). Existing state policy regarding interchange access should be followed.

## TRAFFIC CONTROL DEVICES

The design of an intersection is supplemented by traffic control devices that provide information to the road user about what is expected. The *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) (*59*) provides information on the standards by which traffic signs, road surface markings, and signals are designed, installed, and used. This section provides insights into how the principles and material in the TMUTCD (*59*) can be applied to alternative intersections or roundabouts.

The TMUTCD contains material on guide and regulatory signs for jughandles, trailblazer signs, and roundabouts that can be used along with the material for conventional intersections to develop a signing and marking strategy for alternative intersections. The TMUTCD uses the term "jughandle" for the situation with special geometry where a left-turn or U-turn is made by initially making a right turn. Trailblazer signs were also considered as they provide path confirmation to reach a desired route.

As discussed in Chrysler et al. (*4*), a conceptual distinction for an alternative intersection (or roundabout) signing strategy is the need to provide a step-by-step "trail of breadcrumbs." In many ways, following the progression of turns for the through movement is similar to detour signing. Diagrammatic signs, on the other hand, provide a big picture view of the required movements to drivers and may be most appropriate as the initial advance sign. While this type of "big picture" may not be absolutely required in order to follow the breadcrumbs, it may help drivers understand the overall route and reduce erratic weaves and missed turns.

### Signals

Signals used at alternative intersections are similar to signals used at conventional intersections. The signal timing should consider the needs of all users, for example, consideration should be given to avoid excessive wait times for pedestrians who are exposed to wind and weather.

### Pavement Markings

Although an alternative intersection may operate in an unconventional manner, the pavement markings used should be similar to conventional intersections and interchanges. Examples include using a yellow stripe on the left side of the vehicle while using white on the right even when the travel lane has transition to be on the other side of oncoming traffic such as with the DDI or DLT designs. Stop bars, yield bars, and arrow lane markings would be similar between alternative intersections and conventional intersections. Dotted lane-line extensions can be used to help guide motorists through the crossovers.

### U-Turn Signing

The TMUTCD includes information on U-turn signing at intersections in the form of prohibition and right of way, but these signs are intended for use at traditional intersections. U-turn signing (examples shown in Figure 134) discussed in the TMUTCD include the following:

- No U-turn (R3-4) sign, discussed in TMUTCD Section 2B.18 Movement Prohibition Signs.
- No U-turn/No Left Turn (R3-18) sign, discussed in TMUTCD Section 2B.18 Movement Prohibition Signs.
- U-Turn Yield to Right Turn (R10-16) sign, discussed in TMUTCD Section 2B.53 Traffic Signal Signs.
- Right Turn on Red Must Yield to U-Turn (R10-30) sign, discussed in TMUTCD Section 2B.54 No Turn on Red Signs.

The No U-turn or No U-turn/No Left Turn signs are to be installed adjacent to a signal face and viewed by road users in the left-hand lane.

Another section in the TMUTCD that discusses a U-turn-related sign is Section 2B.22A for the Turnaround Only sign (R3-8uT); see Figure 135 for an illustration of the sign. Per the TMUTCD, the sign is to be used where a separate traffic lane is provided to connect the frontage roads on either side of the facility without a driver having to go through the adjacent intersection. Given that it indicates the exclusive turnaround movement that is required from a specific traffic lane, it has been used within alternative intersections for the point where drivers are U-turning from one direction to the other.

Another sign that is used in Texas is the TURNAROUND sign. Figure 136 shows the sign that is described in *Standard Highway Sign Designs for Texas* (*60*).


**From TMUTCD Figure 2B-4**


**From TMUTCD Figure 2B-4**


**From TMUTCD Figure 2B-27**


**From TMUTCD Figure 2B-27**

Source: TMUTCD 2014 Edition, Figure 2B-4 and Figure 2B-27, page 60 and 97.

**Figure 134. Example of U-Turn Signs Included in the TMUTCD (*59*).**


Source: TMUTCD 2014 Edition, Figure 2B-4, page 60.

**Figure 135. Example of U-Turn Turnaround Only Sign Included in the TMUTCD (*59*).**


Source: *Standard Highway Sign Designs for Texas* 2012 Edition—Revision 2, Page 3-124.
**Figure 136. Example of TURNAROUND Sign (*60*).**

### Trailblazer Signing

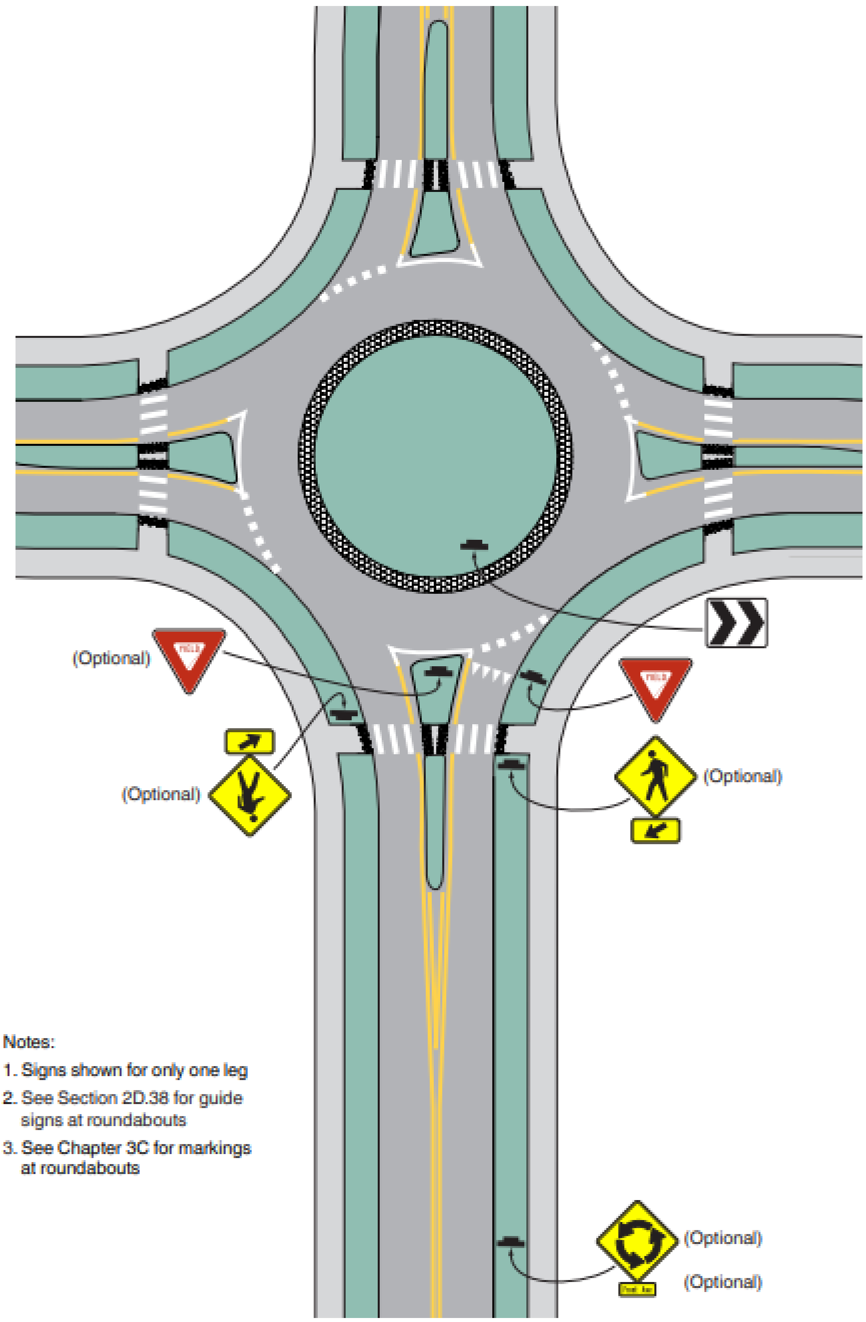
As discussed in Chrysler et al. (*4*), once drivers are forced to turn right when their desired path was a left turn, they may seek confirmation that they are still on a path to their desired route. Trailblazer signs serve this purpose in the TMUTCD. Section 2D.35 of the TMUTCD addresses trailblazer assemblies that "provide directional guidance to a particular road facility from other highways in the vicinity." Typically, these are route marker assemblies with the addition of a TO plaque (M4-5) on the top of the assembly. The use of the word TO is to inform motorists that the road where the sign is posted is not actually the posted route but that it is directing them to the posted route. These assemblies may also include cardinal directions and directional arrows. Figure 137 shows an example of an assembly.


Source: TMUTCD 2014 Edition, Parts from Figure 2D-4 and Figure 2D-6, page 151 and 156.
**Figure 137. Example of a Trailblazer Route Marker Assembly (*59*).**

**Roundabout Signing**

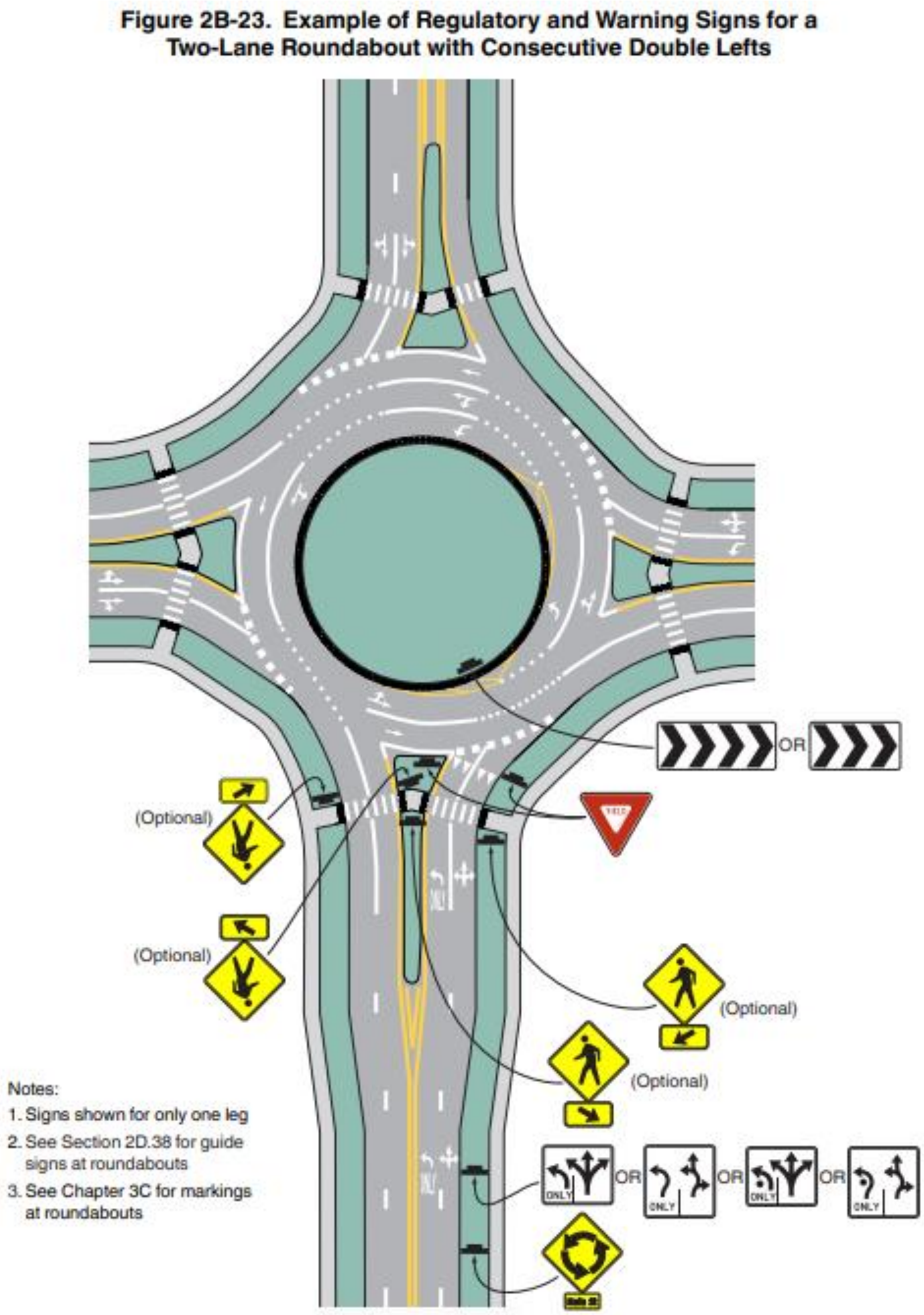
Figure 138 and Figure 139 illustrate the use of regulatory and warning signs at single and double lane roundabouts available in the TMUTCD. The deflection to the right in order to accomplish a left-turn maneuver shares some features with intersections that require U-turns. Left-turning drivers do not expect the rightward movement on approach to either type of intersection without some advance guidance or warning.

Figure 2B-22. Example of Regulatory and Warning Signs for a One-Lane Roundabout




Source: TMUTCD 2014 Edition, Figure 2B-22, page 86.

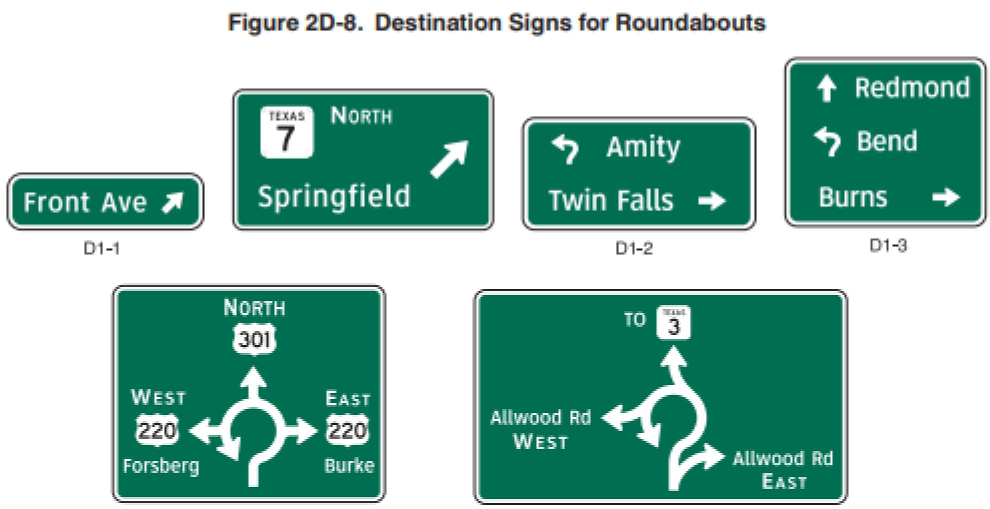
**Figure 138. TMUTCD Figure on One-Lane Roundabout Regulatory and Warning Signs (*59*).**




Source: TMUTCD 2014 Edition, Figure 2B-23, page 87.

**Figure 139. TMUTCD Figure on Two-Lane Roundabout Regulatory and Warning Signs (*59*).**

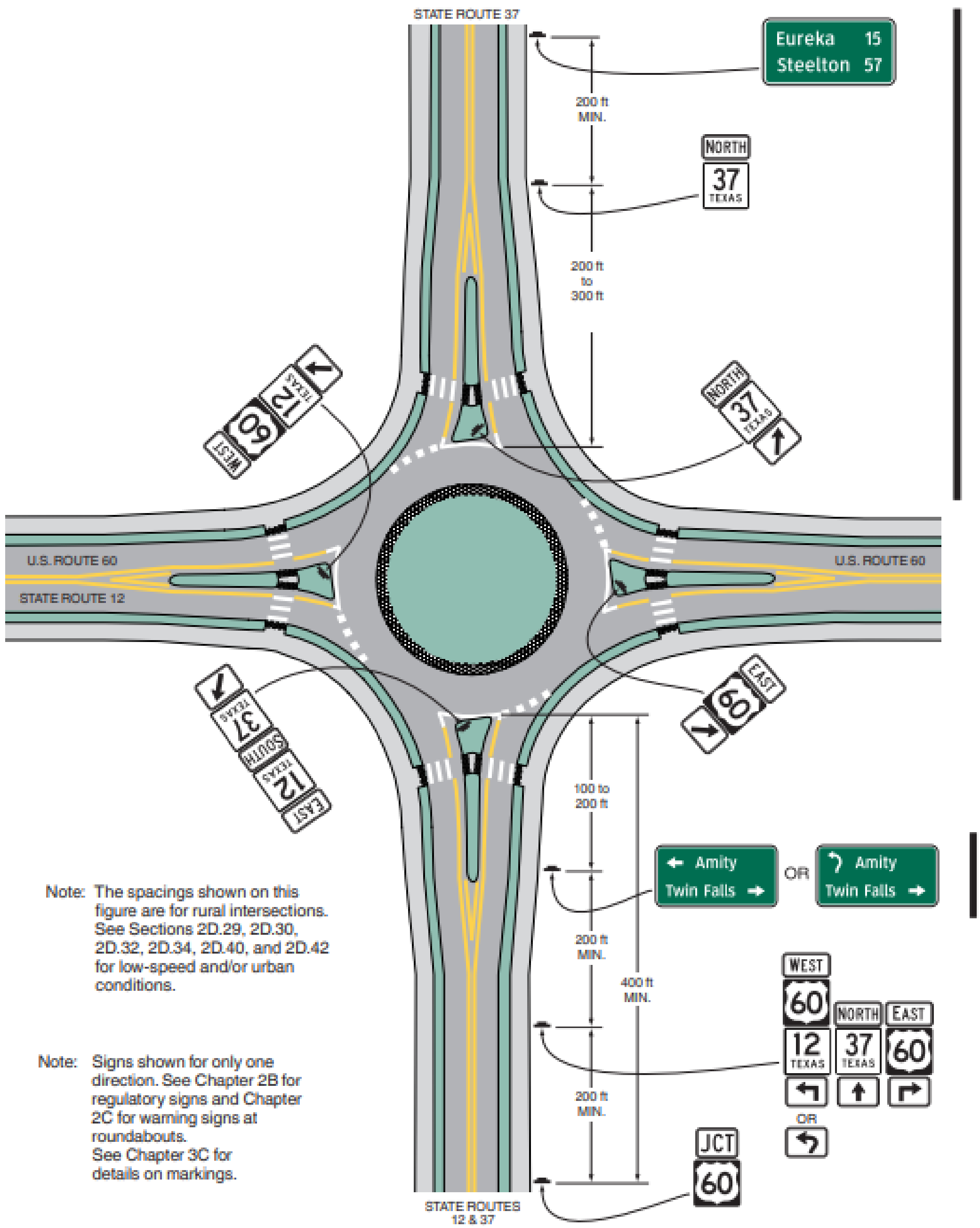
Aside from regulatory and warning signs, destination signs with diagrammatic directional arrows are used to inform drivers of destination points and their direction. Destination signs used for roundabouts are shown in Figure 140. TMUTCD recommends that if the curved-stem arrows are used on destination signs, they should be used consistently with regulatory lane-use signs, directional assemblies, and pavement markings. Additionally, signing examples are shown in Figure 141 and Figure 142 where destination guide signs are installed ahead of the roundabout as well as route markers with directional arrows.




Source: TMUTCD 2014 Edition, Figure 2D-8, page 164.

**Figure 140. TMUTCD Figure on Roundabout Destination Guide Signs (*59*).**

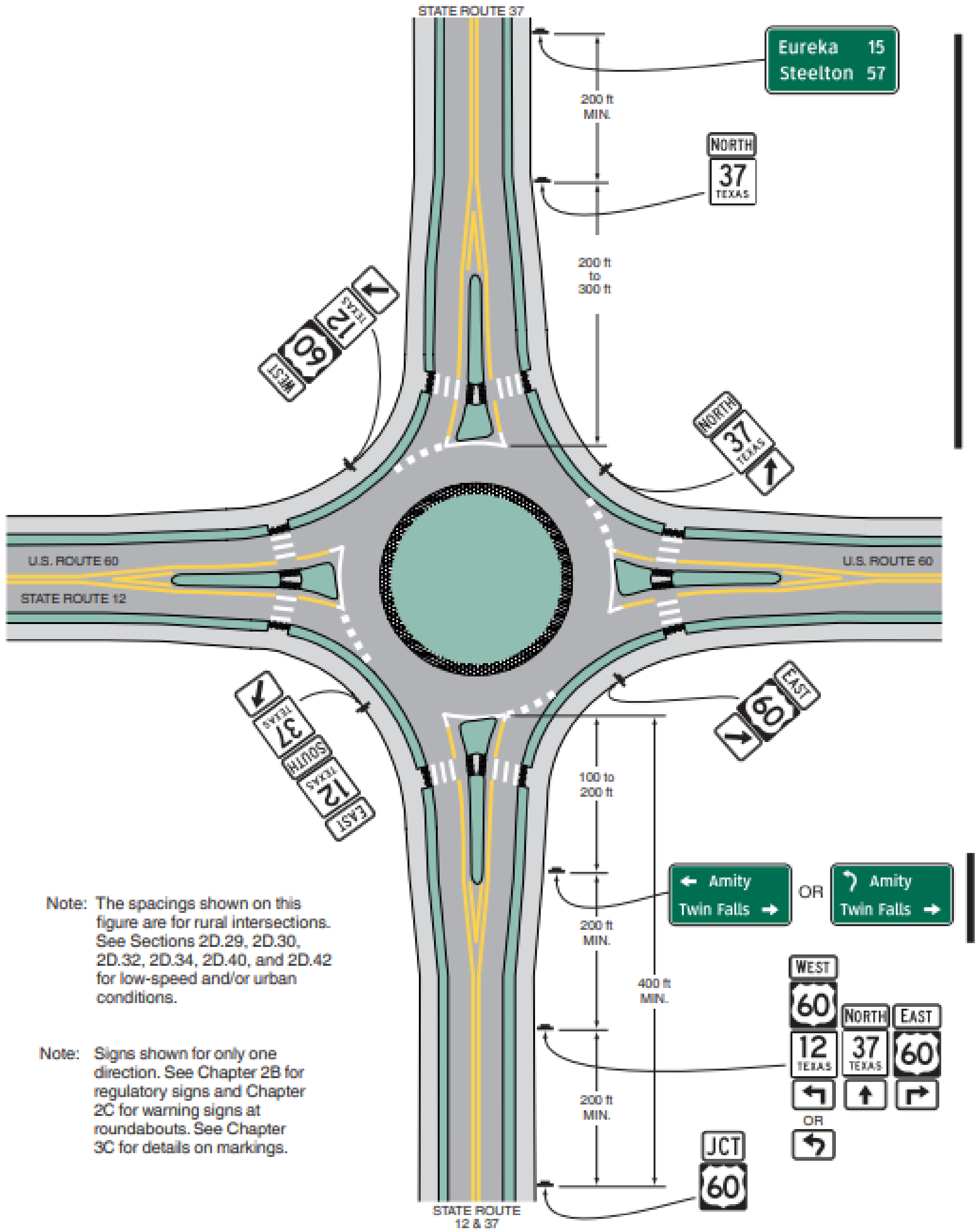
**Figure 2D-9. Examples of Guide Signs for Roundabouts** (Sheet 1 of 2)




Source: TMUTCD 2014 Edition, Figure 2D-9 (sheet 1 of 2), page 166.

**Figure 141. TMUTCD Figure on Roundabout Destination Guide Signs, 1 of 2 (*59*).**

Figure 2D-9. Examples of Guide Signs for Roundabouts (Sheet 2 of 2)



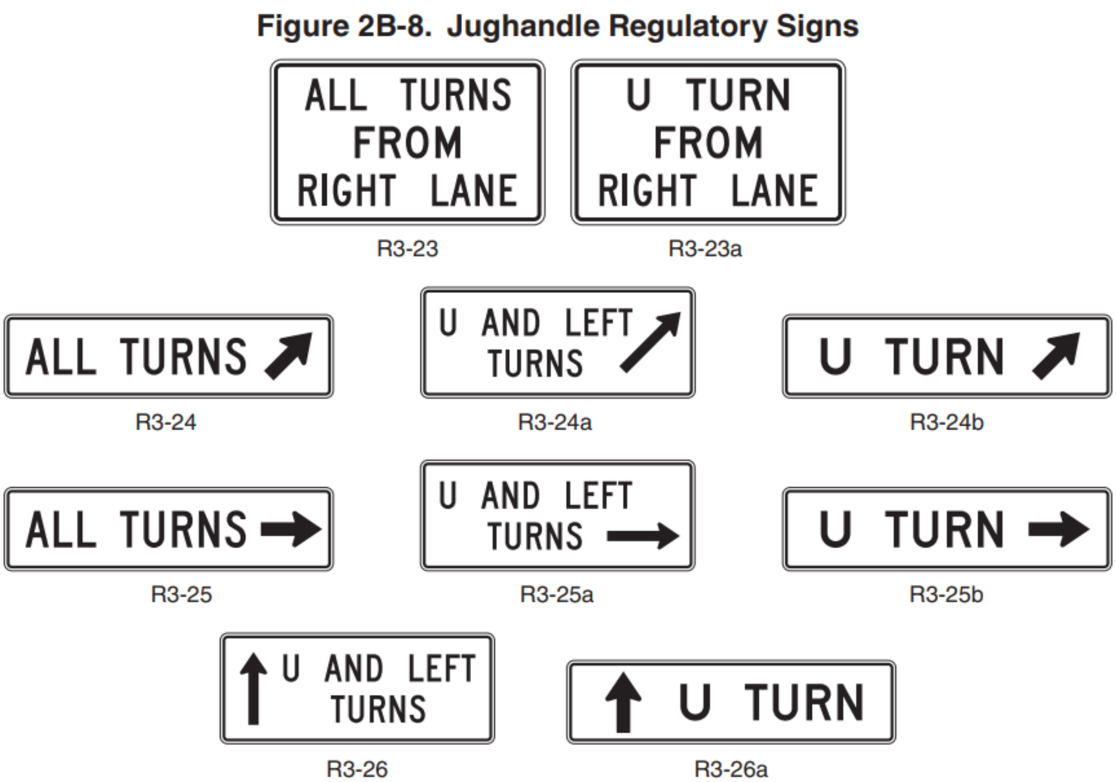

Source: TMUTCD 2014 Edition, Figure 2D-9 (sheet 2 of 2), page 167.

**Figure 142. TMUTCD Figure on Roundabout Destination Guide Signs, 2 of 2 (*59*).**

## Jughandle Signing

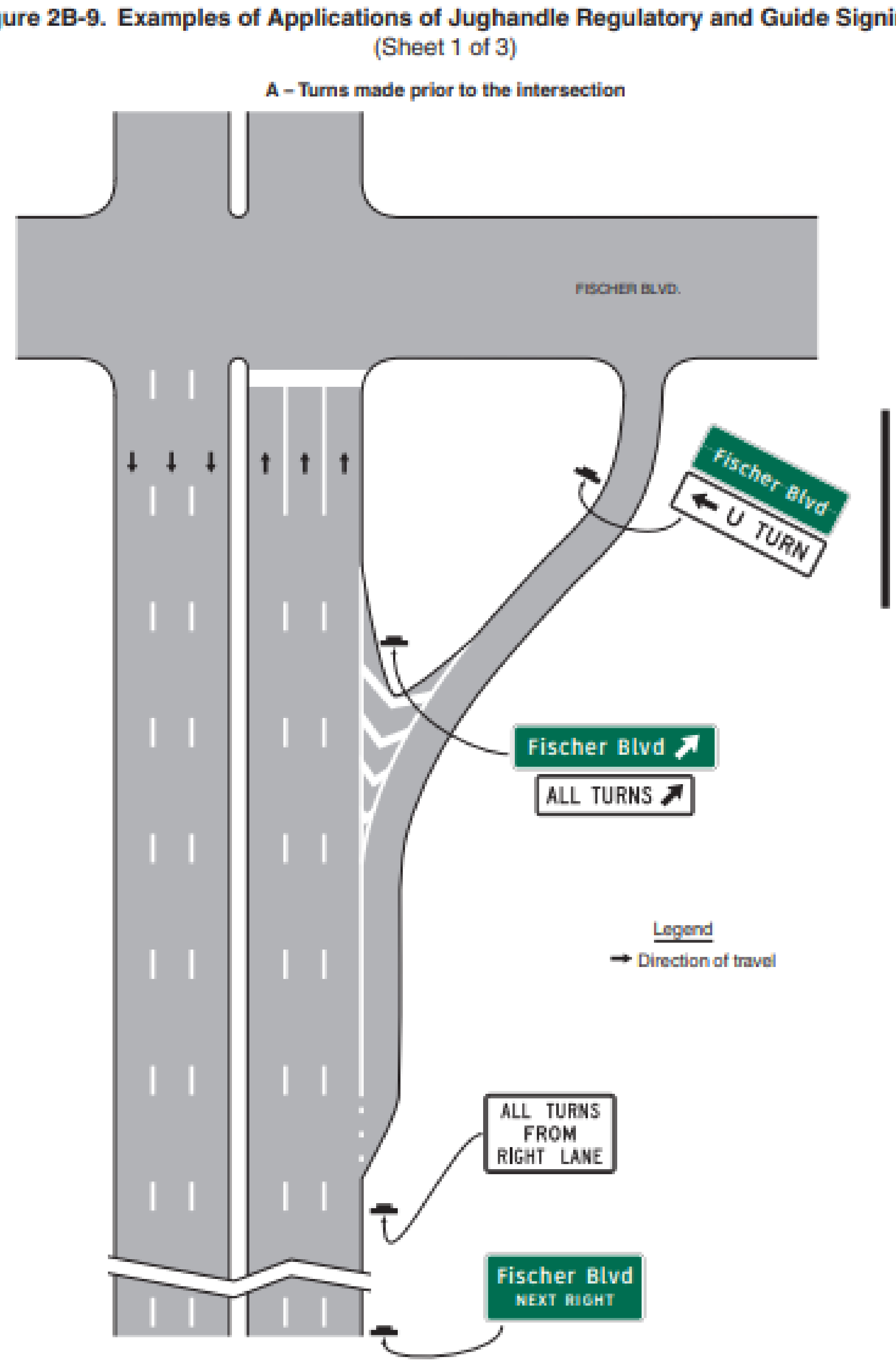
The TMUTCD in Section 2B.27 uses the term “jughandle” for the situation with special geometry where a left-turn or U-turn is made by initially making a right turn. The TMUTCD notes that “this type of turn can increase the operational efficiency of a roadway by eliminating the need for exclusive left-turn lanes and can increase the operational efficiency of a traffic control signal by eliminating the need for protected left-turn phases.” Figure 143 shows regulatory signs for a jughandle intersection.

The TMUTCD provides three examples of signing schematics for jughandle turns (reproduced as Figure 144, Figure 145, and Figure 146 in this document). In addition to these regulatory signs, TMUTCD Section 2D.39 address the use of destination signs at jughandles. Because of the unique nature of jughandle turns the TMUTCD states in Section 2D.39: “If engineering judgment indicates that standard destination signs alone are insufficient to direct road users to their destinations at a jughandle, a diagrammatic guide sign depicting the appropriate geometry may be used to supplement the normal destination signs.”



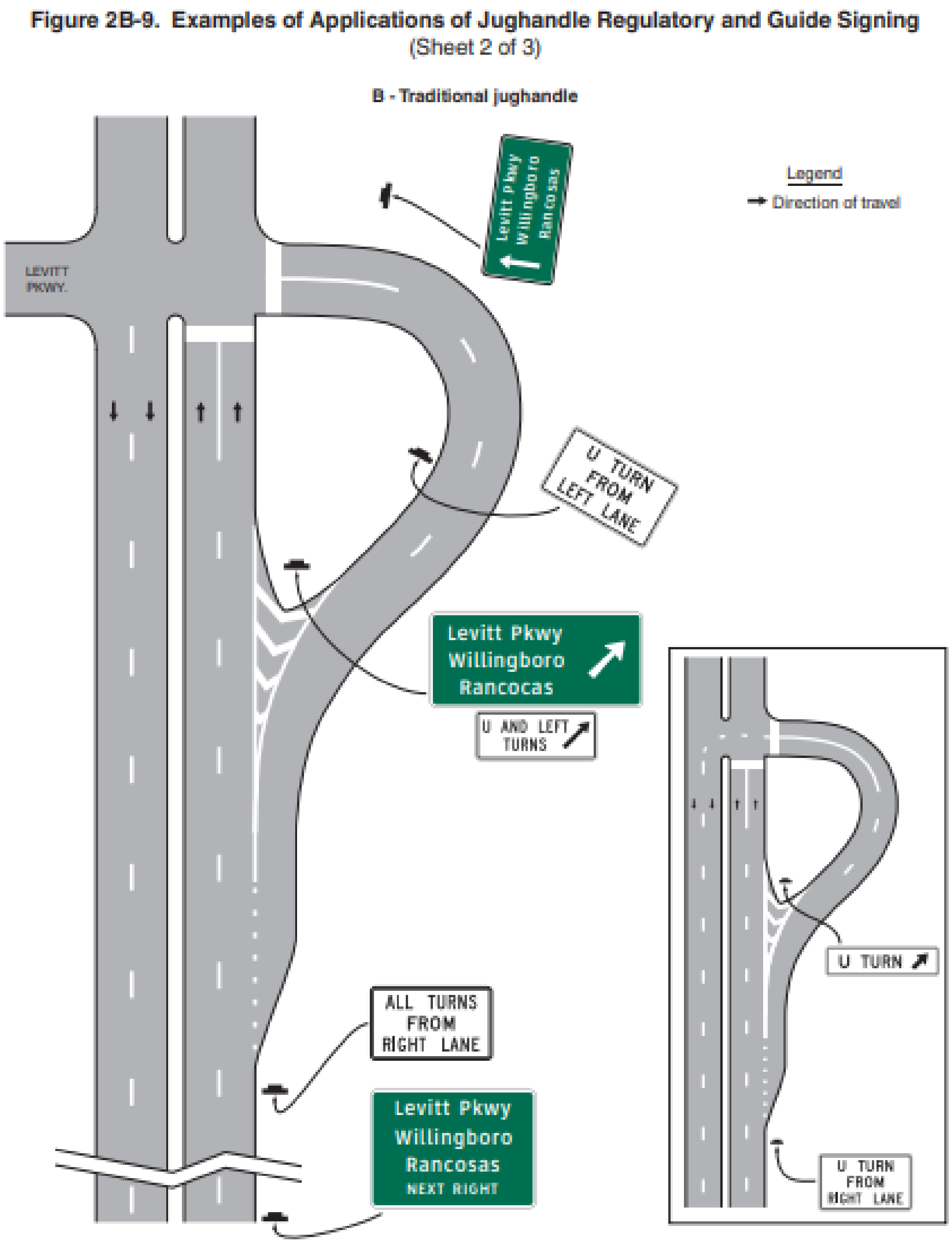

Source: TMUTCD 2014 Edition, Figure 2B-8, page 68.

**Figure 143. TMUTCD Figure on Jughandle Regulatory Signs (*59*).**



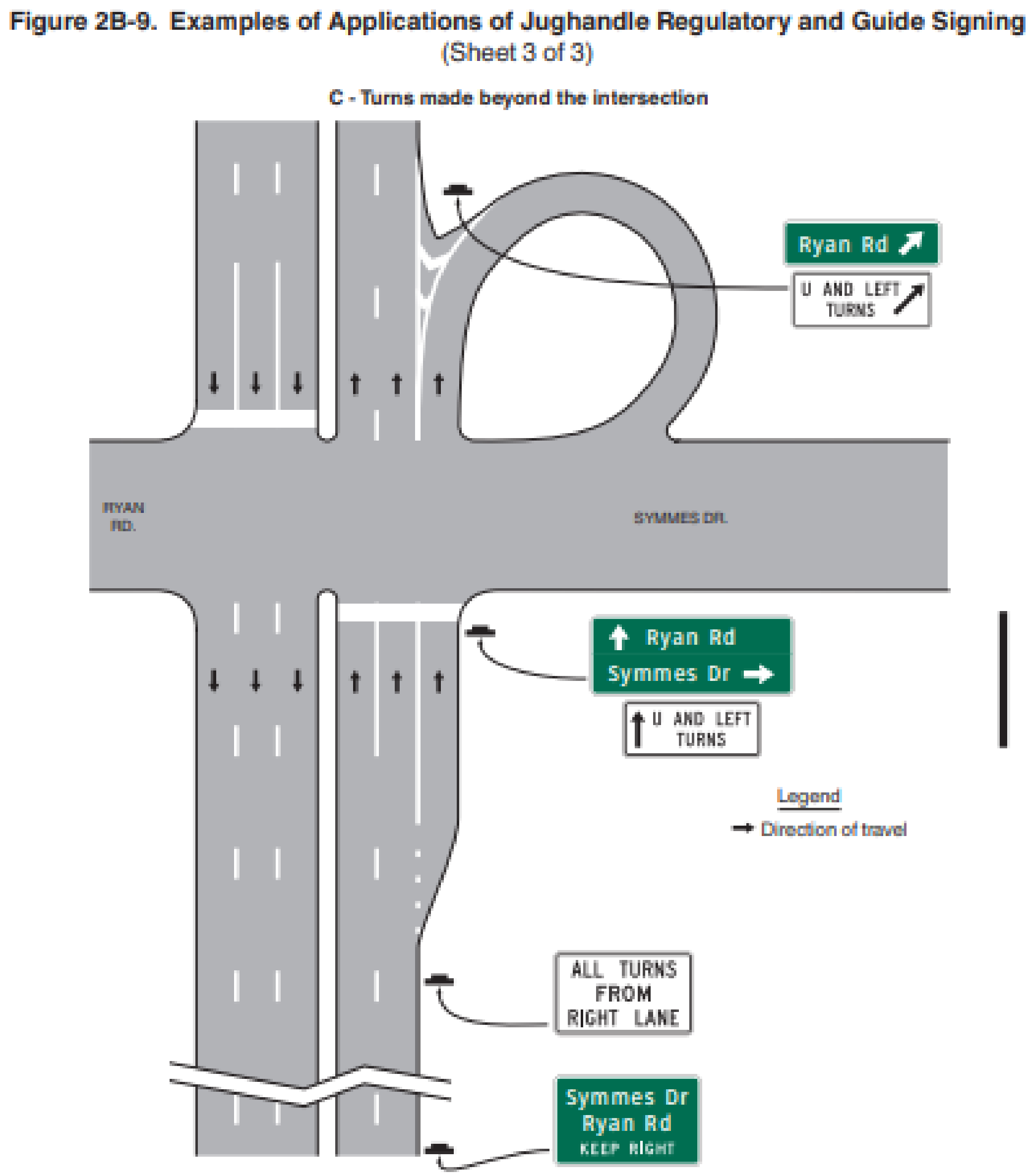

Source: TMUTCD 2014 Edition, Figure 2B-9 (Sheet 1 of 3), page 69.

**Figure 144. TMUTCD Figure on Jughandle Regulatory and Guide Signing, 1 of 3 (*59*).**




Source: TMUTCD 2014 Edition, Figure 2B-9 (Sheet 2 of 3), page 70.

**Figure 145. TMUTCD Figure on Jughandle Regulatory and Guide Signing, 2 of 3 (*59*).**




Source: TMUTCD, 2014 Edition, Figure 2B-9 (Sheet 3 of 3), page 71.

**Figure 146. TMUTCD Figure on Jughandle Regulatory and Guide Signing, 3 of 3 (*59*).**

The example application for jughandles in Figure 144, Figure 145, and Figure 146 share several signing principles:

- Advance guide sign announcing upcoming cross street.
- KEEP RIGHT message included on advance guide sign.
- Advance regulatory sign indicating all turns from right lane at start of turn lane.

- Regulatory sign at gore or intersection with directional arrow to location for U- and left turns.
- Confirmatory guide sign with destination and directional arrow at gore or intersection location.

### Guide Signing

Less direction is provided in reference documents on guide signing for the unique conditions at alternative intersections. The Missouri DOT (MoDOT) document *Missouri's Experience with a Diverging Diamond Interchange—Lesson Learned* (*53*) states that primary and secondary guide signs should not be condensed or combined. Providing a cardinal direction and a destination is typical for a primary guide sign along with using larger legends and route shields. The larger size permits the sign to be visible from a greater distance resulting in more time for drivers to make decisions. Secondary guide signs supplement the primary guide signs and confirm that the driver has made the correct lane decision by providing the route information. Missouri suggests that, as with other complex intersections, the guide signs at alternative intersections should be mounted overhead to increase visibility. In addition, the overhead installation permits the placement of signs directly over the appropriate lane for the specific destinations, which could help communicate to drivers which lane to select. Missouri suggested that the destination information is very important because many drivers more readily look for a destination name rather than knowing their cardinal directions.

## KEY REFERENCES

### Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD)

- **Source:** https://mutcd.fhwa.dot.gov/.
- **Date**: Last modified December 2009.
- **Publisher**: FHWA.
- **Description**: The MUTCD is the national standard for signing on all highways.

### Texas Manual on Uniform Traffic Control Devices for Streets and Highways

- **Source:** https://www.txdot.gov/government/enforcement/signage/tmutcd.html.
- **Date**: Last modified 2011.
- **Publisher**: Texas Department of Transportation.
- **Description**: The TMUTCD is the standard for signing on Texas highways.

### Standard Highway Sign Designs for Texas

- **Source:** http://ftp.dot.state.tx.us/pub/txdot-info/trf/shsd-2012-complete_060512.pdf.
- **Date**: Last modified March 2017.
- **Publisher**: Texas Department of Transportation.
- **Description**: The *Standard Highway Sign Designs for Texas* document includes detailed drawings of signs prescribed or provided for in the TMUTCD. The drawings are for use by all traffic authorities, agencies, jurisdictions, and persons involved with the fabrication, installation, and maintenance of traffic signs on streets and highways in the state.

### Texas Roadway Design Manual

- **Source:** http://onlinemanuals.txdot.gov/txdotmanuals/rdw/index.htm.
- **Date**: Last modified April 2018.
- **Publisher**: Texas Department of Transportation.
- **Description**: The *Roadway Design Manual* was developed by the Texas Department of Transportation to provide guidance in the geometric design of roadway facilities. The *Roadway Design Manual* represents a synthesis of current information and operating practices related to the geometric design of roadway facilities.

### Texas Access Management Manual

- **Source:** http://onlinemanuals.txdot.gov/txdotmanuals/acm/index.htm.
- **Date**: Last modified July 2011.
- **Publisher**: Texas Department of Transportation.
- **Description**: The *Access Management Manual* contains access management criteria that are applicable to all classes of state highways. This manual also provides a mechanism for municipalities to be granted permitting authority to the state highway system.

**NCHRP Report 948—Guide for Pedestrian and Bicyclist Safety at Alternative and Other Intersections and Interchanges**

- **Source:** https://www.trb.org/Main/Blurbs/181781.aspx.
- **Date**: 2021.
- **Publisher**: NCHRP.
- **Description**: NCHRP Report 948 is a guide for transportation practitioners to improve non-motorized user safety at every intersection through planning, design, and operational treatments. The guide provides a "20 flag" method intended to highlight design characteristics that impact safety and quality of service for people walking and biking regardless of the intersection type. Examples include tight walking environments, nonintuitive motor vehicles movements, grade changes, and motorists crossing bicycle paths. Each of the 20 flags include thresholds for a yellow flag and a red flag at a given intersection. A yellow flag is generally associated with user comfort and a red flag with safety. The list is meant to be used both as a comparison tool when selecting between various intersection alternatives as well as a guide for practitioners in the design process, highlighting areas of concern.

**NCHRP Report 672—Roundabouts: An Informational Guide, Second Edition**

- **Source:** http://www.trb.org/Publications/Blurbs/164470.aspx.
- **Date**: 2010.
- **Publisher**: NCHRP / FHWA.
- **Description**: TRB's NCHRP Report 672—*Roundabouts: An Informational Guide, Second Edition* explores the planning, design, construction, maintenance, and operation of roundabouts. The report also addresses issues that may be useful in helping to explain the trade-offs associated with roundabouts. This report updates the U.S. Federal Highway Administration's *Roundabouts: An Informational Guide*, based on experience gained in the United States since that guide was published in 2000.

**Median U-Turn Intersection Informational Guide**

- **Source:** https://safety.fhwa.dot.gov/intersection/rltci/fhwasa14069.pdf.
- **Date**: 2014.
- **Publisher**: FHWA.
- **Description**: This document provides information and guidance on MUT intersections, resulting in designs suitable for a variety of typical conditions commonly found in the United States. To the extent possible, the guide provides information on the wide array of potential users as it relates to the intersection form. This guide provides general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing MUT intersections.

**Restricted Crossing U-Turn Intersection Informational Guide**

- **Source:** https://safety.fhwa.dot.gov/intersection/rltci/fhwasa14070.pdf.
- **Date**: 2014.

- **Publisher**: FHWA.
- **Description**: This document provides information and guidance on RCUT intersections. To the extent possible, the guide addresses a variety of conditions found in the United States to achieve designs suitable for a wide array of potential users. This guide provides general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing RCUT intersections.

**Displaced Left Turn Intersection Informational Guide**

- **Source:** https://safety.fhwa.dot.gov/intersection/alter_design/pdf/fhwasa14068_dlt_infoguide.pdf.
- **Date**: 2014.
- **Publisher**: FHWA.
- **Description**: This document provides information and guidance on the DLT intersection. To the extent possible, the guide addresses a variety of conditions found in the United States to achieve designs suitable for a wide array of potential users. This guide provides general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing DLT intersections.

**Diverging Diamond Interchange Informational Guide**

- **Source:** https://www.trb.org/Main/Blurbs/181562.aspx.
- **Date**: Last updated 2021 (second edition).
- **Publisher**: FHWA.
- **Description**: This document provides information and guidance on the DDI. To the extent possible, the guide addresses a variety of conditions found in the United States to achieve designs suitable for a wide array of potential users. This guide provides general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing DDIs.

**Alternative Intersections and Interchanges Informational Report**

- **Source:** https://www.fhwa.dot.gov/publications/research/safety/09060/
- **Date**: 2010.
- **Publisher**: FHWA.
- **Description**: Today's transportation professionals are challenged to meet the mobility needs of an increasing population with limited resources. At many highway junctions, congestion continues to worsen. Drivers, pedestrians, and bicyclists experience longer delays and greater exposure to risk. Today's traffic and safety problems are more complex and complicated. Conventional intersection/interchange designs are sometimes found to be insufficient to mitigate transportation problems. Consequently, many engineers are investigating and implementing innovative treatments in an attempt to think outside the box. This report covers four intersection designs and two interchange designs that may offer additional benefits compared to conventional at-grade intersections and grade-separated diamond interchanges.

The six alternative treatments covered in this report are DLT intersections, RCUT intersections, MUT intersections, quadrant roadway intersections, double crossover diamond interchanges, and DLT interchanges. The information presented in this report provides knowledge of each of the six alternative treatments including salient geometric design features, operational and safety issues, access management issues, costs, and construction sequencing and applicability.

**Facility Design Guide**

- **Source:** https://roaddesign.dot.state.mn.us/facilitydesign.aspx.
- **Date**: 2021.
- **Publisher**: MnDOT.
- **Description**: Chapter 6E of this document provides discussion on various circular intersections and detailed guidance on the design of roundabouts. It provides an example of a state-level design manual chapter for roundabouts, covering design elements and principles, evaluation and selection criteria, scoping, geometric design details, traffic control devices, lighting, and landscaping. Chapter 6D is the corresponding chapter for reduced-conflict intersections.

**Alternative Intersection Design and Selection**

- **Source:** https://www.trb.org/Main/Blurbs/180649.aspx.
- **Date**: 2020.
- **Publisher**: NCHRP.
- **Description**: State departments of transportation (DOTs) often encounter public resistance to alternative intersections; 86 percent of respondents in a survey of state DOTs agreed or strongly agreed that public resistance hinders their implementation. Public resistance can vary among projects based on intersection type and whether the project was initiated at the local or state level. *NCHRP Synthesis 550: Alternative Intersection Design and Selection* documents the evaluation and selection processes within state DOTs for intersection projects.

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