DEPARTMENT OF TRANSPORTATION

Improving Safety for People Walking and Biking at Roundabouts

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Roundabouts have been shown to enhance safety by lowering travel speeds as compared to other intersection designs. However, pedestrian and bicyclist crossings at roundabouts present unique challenges. Low yielding rates can heighten the risk of crashes, especially at entry and exit points. This study examines driver yielding behavior toward pedestrians and bicyclists at roundabout entry and exit points. Additional analyses compare vehicle speeds on the entry approach in the presence and absence of pedestrians and bicyclists at the roundabout crossing. Crossing events were staged at 16 roundabouts in Minnesota, with driver yielding behavior toward vulnerable road users recorded using video cameras. At nine of these locations, vehicle speed profiles at roundabout entries were also measured using lidar guns. Mixed-effects logistic regression and multiple linear regression models were developed to examine factors influencing yielding behavior and speed selection across different scenarios. The results showed differences in yielding behavior at the roundabout entry and exit, as well as differences based on crossing direction, roundabout geometry, and the presence of rectangular rapid flashing beacons. Additionally, speed selection varied depending on whether vulnerable road users were waiting to cross at the roundabout entry and how drivers responded to their presence.

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Final Report

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Executive Summary

Roundabouts are becoming increasingly popular in the United States. As of recent estimates, there are more than 10,000 roundabouts in the US, a number that has grown from fewer than 50 in 1997. This exponential growth in the number of roundabouts has largely been driven by research that has shown roundabouts to be safer for motorists compared to a traditional signalized intersection. However, modern roundabouts require entering drivers to yield to both the traffic in the roundabout as well as to any vulnerable road user (VRU) present at the crosswalk. This introduces a different set of risks for people who are walking and biking at roundabouts. Research investigating the interaction of motor vehicles with VRUs at roundabout crosswalks is limited, which may be due in part to lower levels of pedestrian and bicyclist activity at locations where roundabouts are commonly implemented, particularly outside of dense urban areas. This research aims to advance our understanding of road user behavior and identify opportunities to improve safety and operations for all users at roundabouts. To that end, there are two primary objectives of this research: evaluate the yielding behavior of drivers toward pedestrians and bicyclists at roundabout crosswalks on both the entry and exit legs; and examine their speed selection behavior as drivers approach a roundabout both in the presence and absence of a pedestrian or bicyclist.

This study involved field evaluations at 16 roundabout locations in Minnesota. These locations were identified in consultation with the Technical Advisory Panel (TAP) and included roundabouts located in urban or suburban areas and represented a diverse group of sites based on traffic volume and roundabout geometry. Sites with advanced traffic control devices such as a rectangular rapid flashing beacon (RRFB) were also prioritized during the site selection process. At each of these sites, 100 crossing events were staged and the yield response of drivers was recorded using video cameras. These events were equally distributed between entry and exit legs and pedestrians and bicyclists. Speed data on the approach leg were collected at nine of the sites using a handheld lidar gun, which recorded continuous speed profiles of vehicles as they approached the roundabout crosswalk.

Most sites showed yielding rates on roundabout entry exceeding 80%, with a few exceptions. In contrast, yield rates on the exit leg were significantly lower with average yield rate lower than 40%. To discern the factors affecting yield rates, random effects logistic regression models were estimated. Analyses were conducted at two levels of detail — separate models for entry and exit legs and a combined model for all the events. Results showed significant differences in yield rates based on site characteristics as well as characteristics of the crossing event. Yield rates were higher toward pedestrians compared to a bicyclist. Yield rates were also higher when the crossing initiated from splitter island or exclusive right turn island compared to the curb. Yield rates were generally higher when the intention to cross was accompanied by the activation of the RRFB. Interestingly, the sites that included RRFBs tended to show higher yielding rates even when the device was not activated. The yielding response of the driver was also found to be influenced by the behavior of drivers in the adjacent lanes. The results also showed yield rates to be significantly lower on double-lane roundabouts and/or roundabouts with two travel lanes on the approach or exit. Other factors such as vehicle lane position, lane width, and vehicle exit point also influenced yielding behavior.

To examine the speed selection behavior of drivers on the entry approach, random effects linear regression models were developed for three scenarios: (1) vehicles that yielded to a VRU present at the crosswalk; (2) vehicles that did not yield to a VRU; and (3) vehicles that approached in the absence of a VRU. The spatial trends revealed that drivers generally start to brake more rapidly when they are within 450-ft of the crosswalk. The average rate of speed reduction among drivers who yielded was about 1.3 mph (1.9 ft/s) for every 50 ft between 200 and 450 ft upstream of the roundabout crosswalk. Likewise, speed was reduced by 5 mph (7.3 ft/s) for every 50 ft when drivers were within 200 ft of the roundabout. Similar trends were observed when vehicles did not yield to VRUs, but the rate of speed reduction was lower (3.3 mph or 4.8 ft/s) within 200 ft of the roundabout crosswalk. Overall, the results indicated that vehicles that did not yield also tended to have higher approach speeds. When VRUs were not present at the crosswalk, the rate of speed reduction was about 0.8 mph (1.2 ft/s) for every 50 ft between 600 and 200 ft upstream of the roundabout crosswalk. As vehicles moved within 200 ft of the roundabout, the speed reduction becomes more rapid, with drivers reducing their speed by 3.3 mph (4.8 ft/s) for every 50 ft traveled.

This study provided important insights into the interaction between drivers and non-motorized users at roundabouts. Based on these findings, recommendations were provided to the Minnesota Department of Transportation (MnDOT) and other local agencies to improve yielding behavior at roundabouts, particularly at locations with moderate to high volumes of people walking and biking.

It should be noted that this study did not evaluate the safety of pedestrians and bicyclists at roundabouts using crash data. Instead, yield rates were used as a surrogate measure of safety. It is unclear how well these yield rates correlate to actual crash experience. Future research could evaluate safety of vulnerable road users at roundabouts through a more comprehensive crash-based evaluation.

Chapter 1: Introduction

Roundabouts are a specific type of circular intersection, where traffic yields before entering the intersection, then moves in a designated direction around the central island, which may be counter-clockwise in some countries (e.g., the United States, Canada) and clockwise in others (e.g., UK, Australia), until departing in the desired direction of travel. Roundabouts are becoming increasingly popular in the United States, from fewer than 50 in 1997 (Jacquemart, 1998) to more than 10,000 as of 2024 (Kittelson & Associates, Inc., 2025). The national roundabout database maintained by Kittelson & Associates, Inc. lists 551 roundabouts in Minnesota (MN) as of April 2025 (Kittelson & Associates, Inc., 2025).

This rapid growth has generally been driven by research that has consistently showed that roundabouts improve both the safety and operational performance of intersections under various contexts, as well as long-term cost savings and environmental benefits and delay savings (Bagdade et al., 2011; Elvik, 2003; Ferguson et al., 2019; Gbologah et al., 2019; Hu et al., 2014; Mamlouk & Souliman, 2018; Meneguzzer et al., 2017; Persaud et al., 2001; Rodegerdts et al., 2010, 2010; Russell et al., 2005; Savolainen et al., 2023). Roundabouts are generally considered safer than signalized or uncontrolled intersections, particularly for motorists. Their design encourages lower travel speeds and often includes fewer or narrower lanes, which help manage speeds and reduce the severity of crashes. These features also make certain high-risk crash types, such as head-on and angle collisions, less common at roundabouts compared to traditional intersections.

1.1 Problem Statement and Study Objectives

Modern roundabouts do not generally include a stop sign or a signal to control traffic movement. Instead, a yield sign is placed at the roundabout entry, requiring approaching drivers to yield to other road users. This design configuration introduces unique safety considerations, particularly for people walking and biking at roundabouts. At roundabouts, pedestrians and bicyclists cross using designated crosswalks upstream of the yield line.

Research on the safety impacts of roundabouts on these vulnerable road users is more limited compared to motorists. This is partly due to lower pedestrian and bicyclist activity in the United States compared to other countries. Much of the research related to VRU safety at roundabouts has been conducted in Europe and Australia, where pedestrian and bicycle activity is relatively higher. However, it is unclear how the results from international research may transfer to the US, given the differences in geographical contexts, traffic laws, and road user behavior. Given lower pedestrian and bicyclist volumes, the relative infrequency of crashes does not necessarily serve as a reliable safety measure. In light of this concern, researchers have used other surrogate safety measures at such locations, such as yield rates when motor vehicle drivers encounter VRUs. While low yielding rates can suggest potential safety concerns, it is important to note that yield rates may not reliably reflect actual crash risk.

The yielding behavior of the drivers can vary based on a multitude of factors, including roundabout design, pedestrian visibility, presence of traffic-control devices such as rectangular rapid flashing beacons (RRFBs), and type of pedestrian crossing signage (Godavarthy et al., 2022; Hourdos et al., 2012; Savolainen et al., 2023). Research has shown significantly lower yield rates towards VRUs waiting to cross at roundabout crossings, particularly at exits where yield rates are worse than entry (Godavarthy et al., 2022; Hourdos et al., 2012). These statistics motivate further research to advance our understanding of road user behavior and identify opportunities to improve safety and operations for all users at roundabouts, given their increasing prevalence. To that end, this research aims to answer the following questions:

1. What percentage of drivers yield to people walking and biking at roundabout entry and exit approaches?
2. Are there differences in yielding rates based on various traffic control devices (e.g., RRFB) or site-specific characteristics?
3. Do drivers make a complete stop when yielding? Alternatively, do they slow down and yield, slow down and not yield, or not slow down at all?
4. How does a driver's speed selection behavior vary in the presence (absence) of people walking or biking?
5. What measures can be taken to improve the safety of people walking and biking at roundabouts?

More specifically, this research evaluates motorists' speed selection and yielding behavior toward people walking and biking at roundabout crossings on the entry and exit approaches through a series of field evaluations. Ultimately, this research provides road agencies with important insights that will enhance the safety of roundabouts for all road users.

1.2 Task Summary

The following tasks were performed as a part of this research effort. A more detailed description of these tasks has been provided in the subsequent chapters of this report.

- Literature Review: A comprehensive state-of-the-art literature review was carried out to document established findings focusing on research on the safety and operational benefits of roundabouts towards VRU. Impacts of special traffic control devices installed at roundabouts, including pedestrian crossing signage, circular flashing beacons, rectangular rapid flashing beacons (RRFB), and pedestrian hybrid beacons (PHB), were also investigated.
- Site Selection: The collaborative effort between the research team and the Technical Advisory Panel (TAP) led to identifying roundabout locations in Minnesota suitable for field evaluations.

- Field Data Collection: This chapter provides a comprehensive overview of the procedures employed to conduct field studies at roundabouts related to the yielding behavior of motorists toward people walking and biking at entry and exit and their speed selection behavior in the presence and absence of these VRUs.
- Data Analysis: This chapter provides the results of the statistical analysis conducted to discern the factors influencing motorists' yielding and speed selection behavior at roundabouts.
- Research Benefits and Implementation Plan: This chapter documents the estimated benefits derived from this project. Details on the key steps needed to implement these benefits are also provided.
- Conclusions and Recommendations: This chapter presents the conclusion and recommendations of the research, followed by the limitations and opportunities for future work.

Chapter 2: Literature Review

A comprehensive review of the extant research literature was conducted to document research and current practices focused on the safety of vulnerable road users at roundabouts. This included research conducted both nationally and internationally. Furthermore, literature on the impacts of various types of traffic control devices typically utilized at roundabouts was also reviewed and summarized. The following sub-sections provide an extensive literature summary and identify trends and gaps in the extant literature.

2.1 International Research on Safety of VRU at Roundabouts

Pedestrian and bicycle activity levels are relatively low at roundabouts in the United States. As such, there are typically relatively few crashes that involve people walking and biking. Consequently, much of the research on pedestrian and bicyclist safety at roundabouts has been conducted in Europe and Australia. Although the number of conflict points at a roundabout is less than a typical four-legged intersection, studies have shown mixed results regarding pedestrian and bicycle safety at roundabouts. For example, in the United Kingdom, the rate of pedestrian-involved crashes at a conventional roundabout was 0.45 crashes per million trips, compared to 0.67 crashes per million trips at signalized intersections (Maycock & Hall, 1984). However, bicycle-involved crashes at roundabouts were higher (2.91 crashes per million trips) than at signalized intersections (1.75 crashes per million trips).

A before-after study from Belgium reported bicyclist injury collisions to increase significantly by 27% and bicyclist fatal and serious injury collisions by 41% (Daniels et al., 2008). A similar study from Denmark investigated bicyclist safety at 332 roundabouts and reported total bike and bike injury crashes to increase by 65% and 40%, respectively (Jensen, 2013b). However, it should be noted that these studies did not consider bike volume at roundabouts due to a lack of data. On the contrary, research from the Netherlands showed a reduction in bicycle crashes after roundabout construction (Dijkstra, 2004).

Additional research from Europe and New Zealand has shown roundabout geometric features, including speed limit, number of approach lanes, entry path radius, and approach capacity to significantly affect bicycle crash injury severity (Akgün et al., 2018), while motor vehicle volume, bicycle volume, moped volume, number of lanes, central radius, apron width, and type of bike crossing and bike lane to affect bike crash frequency significantly (Brude & Larsson, 2000; Daniels et al., 2010, 2011; Hels & Orozova-Bekkevold, 2007; Turner et al., 2009).

Research from Australia and New Zealand has also generally shown similar trends. Failure to yield is the most common error in crashes involving bicyclists, with only 15% of crashes reported as the one where the bicyclist was at fault. Crashes were predominantly found to occur in the circulating lane (Aumann et al., 2017)

A questionnaire study from Denmark reported higher perceived satisfaction towards cycle tracks or paths, blue-painted cycle lanes, and blue-painted crossings (Jensen, 2013a). Another study from Sweden found yield rates towards cyclists to be nearly 60%. This rate was higher at entry than at exits (Christer et al., 2007). Several other studies from across Europe reported perceived risk to bicyclists to be higher at roundabouts compared to intersections, single-lane roundabouts to be safer than turbo and multilane roundabouts, and turbo roundabouts to be safer than two-lane roundabouts (Macioszek & Lach, 2019; Parkin et al., 2007). It was also found that conflicts between circulating cyclists and exiting vehicles were the most dangerous. The most common safety improvement suggestion was to reduce traffic volume, reduce vehicle speeds, and building bike facilities (Møller & Hels, 2008). Research from Canada also reported that the safety perception of roundabouts increases among VRUs if the roundabouts have pedestrian crossings, when traffic volume and speeds are low, and when flashing pedestrian crossing signs are installed compared to other or no signs (Perdomo et al., 2014).

An Australian study also reported increased safety perception among cyclists if roundabouts with in-road bike lanes were converted to protected roundabouts (Tan et al., 2019). An observation-based study from Sweden found yield rates at roundabouts with separated cycle paths to be higher at entry compared to exit when the cyclist was traveling in the same direction as the vehicle (Sakshaug et al., 2010). Another study on yielding toward cyclists at roundabouts recommended that vehicle speeds should be kept below 12 mph (20 km/h) to increase yield rates (Silvano et al., 2015).

2.2 National Research on Pedestrian and Bicyclist Safety at Roundabouts

The research on the safety of people walking and biking, and other VRUs at roundabouts is limited primarily due to the lower frequency of crashes involving such users. Additionally, it is unclear how the results from international research may transfer to the US, given the differences in geographical contexts, traffic laws, and road user behavior. Nevertheless, alternate methodologies have been adopted to evaluate safety of people walking and biking at roundabouts without crash data, including surveys and video data analysis such as vehicle speeds, trajectory, and their interaction with non-motorized road users.

A study conducted at 14 approaches across seven roundabouts in the US found no substantial safety issues for non-motorists at roundabouts in terms of collision or conflicts (Harkey & Carter, 2006). However, the study found exit legs to be of greater risk to pedestrians than entry legs due to lower yielding rates at exits. Differences were also shown across roundabouts with different numbers of approach lanes. On roundabouts with single-lane approaches, 17% of the motorists did not yield to pedestrians intending to cross. On two-lane approaches, 43% of motorists did not yield. However, it should be noted that the statute does not require motorists to yield to pedestrians who are not within the crosswalk. Nevertheless, the study aimed to examine the driver’s response to a pedestrian who is clearly waiting to cross the roundabout. The study also found a few events of bicyclists' wrong-way driving, particularly when entering the roundabout from the exit leg. The study recommended that the design of exit legs should be improved to ensure adequate sight lines and minimum vehicle speeds to improve the safety of non-motorized users.

A Michigan study conducted a detailed field evaluation of 5 roundabouts through staged pedestrian crossings. The study reported yielding rates at entry exceeding 85% on sites located on surface streets. However, sites on ramp terminals showed yield rates of less than 45%, primarily attributed to higher approach speeds of vehicles exiting the freeway (Savolainen et al., 2023). Similar results were also reported from an evaluation conducted in Minnesota that showed that less than 50% of drivers yielded to pedestrians or bicyclists at the entrances to multilane roundabouts. Compliance was even worse at roundabout exits, as only 23% of drivers yielded (Hourdos et al., 2012). A recent study from Minnesota reported that single-lane roundabouts have higher yield rates toward pedestrians than at multilane roundabouts. Additionally, exit legs exhibited lower yield rates compared to entry legs. Higher approach speed was negatively correlated with yield rates (Godavarthy et al., 2022).

A study by the California Department of Transportation found that 32% and 18% of bicyclists and pedestrians, respectively, found navigating a multilane roundabout uncomfortable through a self-reported survey (Arnold et al., 2013). User demographics, such as age, were also found to affect user comfort. Pedestrians equally preferred roundabouts and signalized intersections, while bicyclists preferred signalized intersections over roundabouts and stop-controlled intersections. Video data also showed an inverse relationship between vehicle volume and pedestrian volume, consistent with international research.

While previous studies consistently showed that driver yield rates at roundabout exits are substantially lower than those at entries, it is important to recognize that even these lower exit yield rates may still be relatively favorable when compared to other intersection types, particularly uncontrolled or midblock crossings.

A study conducted in Wisconsin reported a yield rate of approximately 16% on major roads such as arterials and collectors (Schneider et al., 2017). Similarly, a multi-state study reported wide variation in yield rates at uncontrolled crosswalks, ranging from 40–80% in California, 10–70% in Florida, 5–25% in North Carolina, and 40–90% in Oregon (Alston et al., 2023). These sites included both basic and enhanced crosswalk treatments. NCHRP Report 562: *Improving Pedestrian Safety at Unsignalized Crossings* showed significant variability in yield rates across similar sites. Yield rates varied from 10% on 35-mph road to between 60-90% on 25-mph street (Fitzpatrick et al., 2006). Another study evaluated the safety effects of protected left-turn phasing at signals on pedestrian-vehicle crashes but reported no significant benefits (Goughnour et al., 2021). The leading pedestrian interval, however, showed reduction in pedestrian-vehicle crashes with a crash modification factor of 0.87. Another study reported channelized right turns at signalized intersections increase pedestrian risks from various safety perspectives (Jiang et al., 2020).

A recent study conducted in St. Paul and Minneapolis evaluated impacts of various engineering-focused countermeasures on yield rates at both signalized and unsignalized intersections (Morris et al., 2023). The yield rates prior to any implementation of a countermeasure were reported to be between 28% and 67% across 4 treatment sites and 4 control sites in St. Paul. In Minneapolis, yield rates varied between 14% and 48%. Similarly, at signalized intersections, the right-turn yield rates varied from 82-94%, while left-turn yield rates varied from 48-92% across 8 locations in St. Paul (Morris et al., 2023). While direct comparisons are limited due to differences in site characteristics and study methodologies, these figures suggest that roundabout exit crosswalks, despite lower yield rates compared to entries, may still perform better than many other crossing scenarios.

Studies have also investigated factors affecting the yield rates of drivers towards pedestrians with vision impairments. A study from Tennessee investigated pedestrian behavior at roundabouts, which involved six blind and six sighted pedestrians crossing a two-lane urban roundabout (Ashmead et al., 2005). The study found blind pedestrians waited three times longer to cross the roundabout than sighted pedestrians. Driver yield rates were found to be higher on roundabout entry compared to exits. Similar findings were reported by other studies that found yield rates to be higher at low speeds, at entry legs compared to exit legs, and higher towards pedestrians with a white cane compared to sighted pedestrians (Geruschat & Hassan, 2005; Salamati et al., 2013).

In August 2023, the United States Access Board issued the rules related to the Public Right-of-Way Accessibility Guidelines (PROWAG), which went into effect on September 7, 2023 (U.S. Access Board, 2023). PROWAG was developed to support the Americans with Disabilities Act (ADA) and the Architectural Barriers Act (ABA) by addressing access to sidewalks, streets, crosswalks, curb ramps, pedestrian signals, on-street parking, and other components of public rights-of-way. PROWAG also provides details related to treatments at roundabouts. For example, the guidelines state that the cross slope of a pedestrian access route within a crosswalk at a roundabout should not be more than the street grade. The guidelines related to pedestrian paths at roundabouts are summarized below (U.S. Access Board, 2023):

- If a pedestrian crossing is not intended at the roundabout, the pedestrian circular path should be separated from the curb, crosswalk to crosswalk, with landscaping or other surface at least 24 inches wide.
- Detectable warning surfaces should not be used for roundabout edge detection.
- The guidelines state to provide a continuous and detectable vertical edge treatment along the street side of the pedestrian circulation path from crosswalk to crosswalk. This is to be provided where a pedestrian crossing is not intended. The guidelines also state that the bottom edge of vertical edge treatment should not exceed 15 inches above the pedestrian circulation path.
- Each roundabout segment containing the crosswalk should have a crosswalk treatment at multilane roundabouts. This treatment can be any one or more than one from the following list:
    - Traffic control signal with a pedestrian signal head

  - PHB
  - Pedestrian actuated RRFB
  - Raised crossing
- One or more of the above pedestrian crossing treatments are also to be provided on crosswalks at multilane channelized turn lanes at roundabouts.

Additional guidelines related to pedestrian push buttons, pedestrian detection, pedestrian signal walk indications, transit stops and shelters, on-street parking, passenger loading zones, etc., are also provided in PROWAG, which applies to roundabouts.

2.3 Use of Traffic Control Devices to Improve Pedestrian and Bicyclist Safety

The extant research literature discusses several types and combinations of pedestrian crossing signs, traffic control devices, and geometric configurations to improve the safety of VRU across various contexts. However, research pertinent to their effectiveness on roundabouts is rather limited. Nevertheless, consistent efforts are being made to improve the safety of VRUs at roundabouts.

Research from Australia found that bicyclists commonly traveled close to the center of the traffic lane. Bicycle lanes were rarely used in the circulating lanes. In cases where shared lanes were provided, the bicyclists' position was shifted, indicating that the presence of bicycle lanes within the roundabout may serve to discourage lane sharing (Wilke et al., 2014). It was also found that equitable speeds between drivers and bicyclists are desirable from a safety perspective. In such cases, bike lanes on the approach should terminate some distance behind the yield line where speeds are low.

Research has generally found multilane roundabouts to be more challenging to navigate for a pedestrian or bicyclist compared to a single-lane roundabout due to the increased complexity of navigation (Arnold et al., 2013; Aumann et al., 2017; Patterson, 2010; Rodegerdts et al., 2010; Wilke et al., 2014). National Cooperative Highway Research Program (NCHRP) Report 672 also notes that single-lane roundabouts designed for low speeds are the safest treatment possible for at-grade intersections. The report also documents that multilane roundabouts cannot achieve the same level of safety as single-lane roundabouts, and VRUs have to face multiple threats when crossing at both entry and exit (Rodegerdts et al., 2010). The report proposes to minimize travel lanes, design for slower speeds, design sidewalks that are set back from the circulating lanes, and provide a splitter island with a crosswalk that is at least 6-ft wide as some of the measures to increase pedestrian safety in urban and sub-urban settings. Research from Wisconsin also proposes similar solutions to improve the safety of VRU at roundabouts. These include reducing vehicle speeds, reducing sign clutter at roundabouts, proper lighting to ensure critical features are illuminated, use of landscaping to limit excessive sight distance, balanced and multimodal design of roundabouts (FHWA, 2020). NCHRP Report 834 (Schroeder et al., 2017) also provides several solutions to enhance the safety of pedestrians while crossing roundabouts. Although these solutions primarily focus on pedestrians with vision disabilities, the treatments generally apply to roundabouts with VRU activity. These treatments include using staggered crosswalks, raised pedestrian crossings, and installing PHB or RRFB or flashing beacons.

A pedestrian hybrid beacon (PHB) or HAWK signal is a type of traffic control device used to inform drivers when to stop when activated. The Manual on Uniform Traffic Control Devices (MUTCD) provides provisions to install PHB at roundabouts (FHWA, 2022). Generally, PHB and RRFB have been shown to improve driver yielding at crosswalks; additional research is warranted regarding their effects on driver and pedestrian behavior at roundabouts. A national study evaluated the effectiveness of RRFB on yielding behavior toward pedestrians at multilane roundabouts (Schroeder et al., 2015). The yielding behavior was investigated at nine roundabout approaches by comparing yielding behavior when RRFB was activated versus when it was not. At five of the nine approaches, the yielding rates increased by 36-88 percent when RRFB was activated compared to when it was not. However, no significant differences were observed in yielding as a result of RRFB activation.

A simulation-based study reported yielding rates to increase when PHB or RRFB were installed at multilane roundabouts (Salamati et al., 2012). A before-after study from Texas reported noticeable improvements in yielding toward pedestrians when PHB was installed, although only one site was evaluated with PHB (Brewer et al., 2015). The same study also reported yielding rates to increase by 35-79 percent as a result of RRFB installation (Brewer et al., 2015). However, a field study in Michigan evaluated two sites with PHB through staged pedestrian crossing events and found no significant differences in yield rates compared to similar sites without PHB (Savolainen et al., 2023). The study concluded that the PHB installation should be considered on a case-by-case basis and benefit-cost analysis may be conducted to justify PHB installation, given the higher costs associated with PHB.

2.4 Literature Summary

Generally, research has consistently shown that roundabouts improve safety from a motorist's perspective. However, a consensus is still to be reached regarding the safety of vulnerable road users (VRU) at roundabouts. Research from Europe and Australia has shown mixed results. Due to the lack of sufficient pedestrian and bicyclist crash data in the United States, alternate methodologies such as self-reported surveys and surrogate safety measures such as yield rates have been investigated to evaluate safety of people walking and biking at roundabouts.

Overall, research from the US has consistently reported two findings. First, yielding rates toward VRU are significantly lower on roundabout exits than on roundabout entry. Second, multilane roundabouts are more challenging to navigate for people walking and biking and thus are generally perceived to be less safe than a single-lane roundabout. Although traffic control devices such as pedestrian hybrid beacons (PHB) and rectangular rapid-flashing beacons (RRFB) have generally been shown to improve yield rates at roundabouts, additional research is warranted to compare sites under varying contexts. Lastly, much of the research across the United States has focused on pedestrian interaction with vehicles. Investigations into how the driver's behavior and yield rates vary in the presence of people biking at roundabout entry or exit are very limited. Consequently, this study helps fill important gaps in the literature and advance the fundamental knowledge related to driver yielding behavior at roundabouts.

Chapter 3: Site Selection

The investigation into the drivers' speed selection and yielding behavior towards VRU at roundabouts was conducted through field studies. To that end, the research team worked with the Technical Advisory Panel (TAP) members to screen and identify potential roundabouts in the state of Minnesota that would be suitable for field evaluations. The following sections details the site selection procedure and summarizes the characteristics of the sites selected for field evaluations.

3.1 Initial Data Collection

The TAP shared an initial list of 95 roundabouts in the state of Minnesota. This included details such as site coordinates, intersection name, city and county, number of approaches, functional class (at-grade vs grade separated), year of roundabout completion, and type of traffic control prior to roundabout construction. In addition to these data, the research team collected the following information using Google Earth and street view to aid in site selection. The data were collected separately for each approach leg wherever applicable:

- Number of circulating lanes
- Number of legs
- Number of approach lanes
- Number of exit lanes
- Lane width (ft)
- Approach speed limit (mph)
- Roundabout advisory speed
- Pedestrian crossing present (yes/no)
- Vehicle volume (veh/day)
- Roadway context (rural vs sub-urban vs urban)
- Feasibility of collecting lidar speed data
- Type of pedestrian signage on both entry and exit
- Presence of special traffic control device such as RRFB

During this initial data collection, information on the different types of roundabout signage and pedestrian signage present on each of the legs of the roundabout were also recorded. The various types of signage encountered during this initial observation are presented in Table 1.

Table 1 Typical Signage Encountered at a Roundabout

Code	Sign	Remarks
W11-2 (Pedestrian warning sign)		Typically installed at all pedestrian crossings. However, some sites had this sign only at the exit approach.
R1-6a (In-street pedestrian crossing stop sign)		Some sites had this sign along with the W11-2 sign. At a roundabout, this sign is typically placed in the median.

Code	Sign	Remarks
W3-2 (Yield ahead sign)		Only a few sites had this sign installed.
W2-6 with W16-17P and W13-1P (Roundabout symbol, roundabout text, advisory speed)		Most of the time, these three signs are installed together. However, there were several sites that had only a W2-6 sign, while others had a W2-6 sign with a W13-1P sign. The advisory speed ranged between 15 and 25 mph
Rectangular rapid flashing beacon (RRFB)		RRFB is installed only at select sites.

3.2 Site Selection and Summary

Once the relevant data regarding roundabout configuration, type of pedestrian signage, and traffic volume were collected, a list of 16 primary sites was prepared for field evaluations based on the feedback from TAP. These sites were selected based on varying geometry, traffic volume, and pedestrian signage. Priority was given to sites located in urban or sub-urban areas, and sites with electronic traffic control devices such as RRFB. Figure 1 shows the location of the sixteen sites selected on a map. Table 2 presents the list of these 16 sites along with the number of approaches, number of circulating lanes, and the type of treatment.

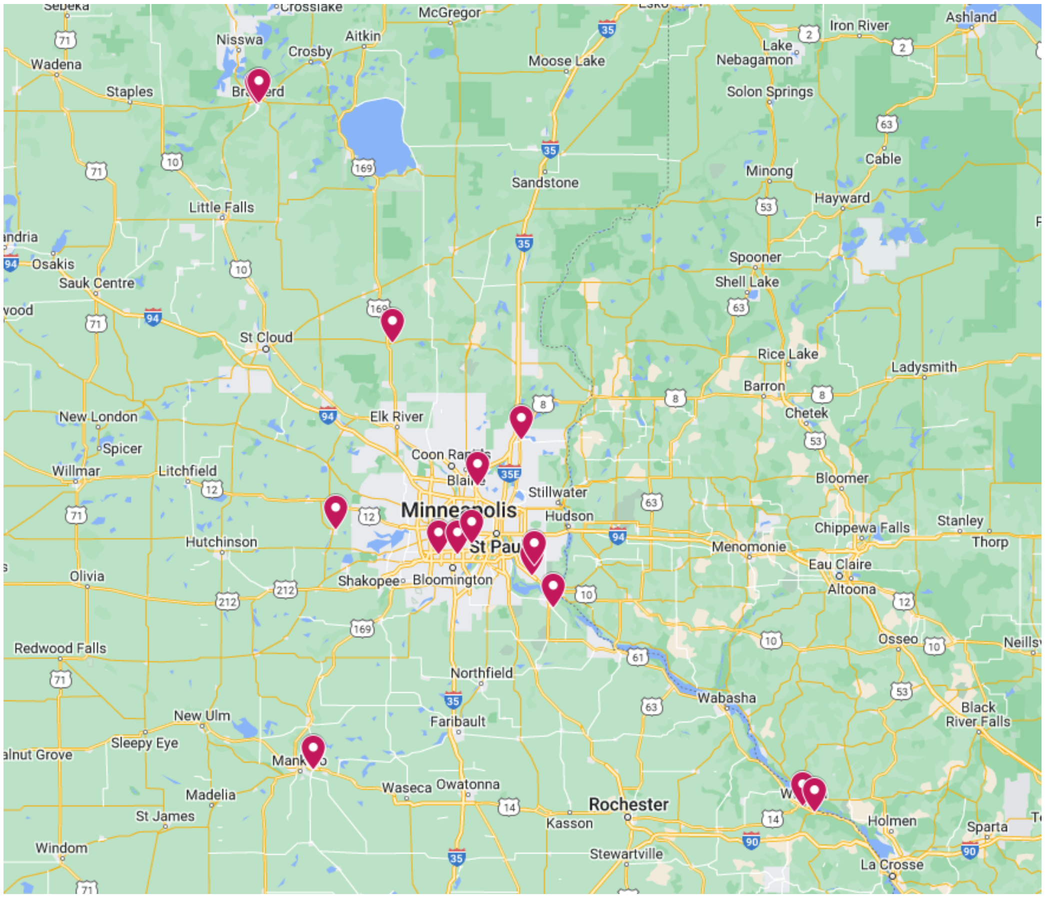

Figure 1 Location of Roundabout Sites for Field Evaluations

Table 2 List of Roundabout Sites for Field Evaluations

Intersection	City (County)	Approaches (Direction of Data Collection)	Lanes at Crosswalk	Treatment
4th St./E College Dr.	Brainerd (Crow Wing)	3 (NB)	Two	W11-2, W2-6, W13-1P, W16-17P
66th St./Nicollet Ave.	Richfield (Hennepin)	4 (EB)	Two	W11-2, R1-6a, W2-6, W13-1P, W16-17P, RRFB
STH 316 (Red Wing Blvd.)/Tuttle Dr.	Hastings (Dakota)	4 (NB)	One	W11-2 (exit), R1-6a, W3-2, W2-6, W13-1P
US 61-US 10/Jamaica Ave S/W Point Douglas Rd S	Cottage Grove (Washington)	5 (ramp)	Two	W11-2 (exit)
Valley View Rd./Tracy Ave./Valley Ln.	Edina (Hennepin)	3 (SB)	One	W11-2, W2-6, W13-1P, RRFB
W College Dr/Mississippi Pkwy-SW 4th St.	Brainerd (Crow Wing)	4 (SB)	One	W11-2, W2-6, W13-1P, W16-17P

Intersection	City (County)	Approaches (Direction of Data Collection)	Lanes at Crosswalk	Treatment
Madison Ave/TH 22	Mankato (Blue Earth)	4 (WB)	Two + exclusive right	W11-2 (exit), R1-6a, W3-2
TH 95/N Rum River Dr	Princeton (Mile Lacs)	4 (WB)	Two	W11-2, W3-2, W2-6, W13-1P, W16-17P
Territorial St E/Lewis Ave N	Watertown (Carver)	4 (EB)	One	W2-6
70th St S/Jamaica Ave S	Cottage Grove (Washington)	4 (WB)	Two	W11-2 (exit), R1-6a, W2-6, W13-1P, W16-17P
I 35/Rice Creek Pkwy-Thumb Rd/CR1	Arden Hills (Ramsey)	5 (WB)	One	W11-2 (exit), W2-6, W13-1P, W16-17P
Gilmore Ave./W Service Dr./US 14 Connector	Winona (Winona)	3 (EB)	One	W11-2, W2-6
US 14/TH 43	Winona (Winona)	4 (EB)	Two	W11-2, RRFB
US 61/TH 97 (North Junction)	Forest Lake (Washington)	4 (WB)	Two + exclusive right	W2-6 (exit), W13-1P
TH 22/Adams St.	Mankato (Blue Earth)	4 (NB)	Two + exclusive right	W11-2 (exit), R1-6a, W3-2
Minnehaha Ave./Godfrey Pkwy.	Minneapolis (Hennepin)	4 (EB)	One	W11-2, R1-6a, W2-6

The final list of 16 locations identified for field evaluation included:

- Three three-legged roundabouts, 11 four-legged roundabouts, and two five-legged roundabouts (also on exit ramps) were finalized for field data collection.
- Seven out of 16 sites were single lane roundabouts, while nine were multilane roundabouts.
- Nine of the sites have equal number of approach lanes on all legs (balanced configuration), while remaining have unequal number of approach lanes on at least two legs (unbalanced configuration).
- All single lane roundabouts had equal number of approach lanes on all legs (balanced). Only two out of ten multilane roundabouts had equal number of approach lanes on all legs (unbalanced).
- Average AADT on single lane roundabouts was 6,420 veh/day, while average AADT on multilane roundabouts was 10,748 veh/day.
- Three of the 16 sites had RRFB. One of the sites (Territorial St. E/Lewis Ave. N) had no pedestrian related signage on either exit or entry.

- Mini roundabouts initially identified for field evaluations were not included in the final list primarily because of very low traffic volume.
- Site located on STH 316/Tuttle Dr. is a newly constructed compact roundabout which is a part of FHWA Highway 316 redesign under Safe Systems approach.

Chapter 4: Field Data Collection

Field evaluations were conducted at all 16 roundabout locations identified during the site selection process. Field data collection activities were primarily performed from August 28, 2023 to September 1, 2023. A second round of data collection was performed between August 26 and August 30, 2024 to collect additional data in order to fill some gaps from the first round of data collection.

The field data collected fell under two general categories:

- Yielding behavior: Data collected as to whether drivers entering or exiting the roundabout yielded to a person intending to cross on foot or on a bike. These data were collected using pole-mounted cameras installed at site.
- Speed selection: Speed profiles were collected from vehicles as they enter each roundabout, both in the presence and absence of a person walking or biking. These data were collected using handheld lidar.

Table 3 presents the list of 16 roundabout sites along with the data collection approach and data collection method. At some of the sites (n=7), lidar data collection was not feasible due to limited parking available on roadside. The detailed methodology adopted to collect speed and yielding behavior data is discussed in the subsequent section. Additional details related to each of the sixteen roundabouts along with aerial image of the site and the street view of the approach are presented in Appendix-A.

Table 3 Data Collection Method at Roundabout Locations

Intersection	City (County)	Data Collection Direction	Data Collection Method
4^{th} St. / E College Dr.	Brainerd (Crow Wing)	4^{th} St (NB)	Camera
E 66^{th} St / Portland Ave (Very limited data collected. Data collected on backup site instead.)	Richfield (Hennepin)	Portland Ave. (NB)	Camera
66th St. / Nicollet Ave.	Richfield (Hennepin)	66^{th} St. (EB)	Camera
STH 316 (Red Wing Blvd.) / Tuttle Dr.	Hastings (Dakota)	STH 316 (NB)	Camera+Lidar
US61-US10 / Jamaica Ave S / W Point Douglas Rd S	Cottage Grove (Washington)	US-10 exit ramp (EB)	Camera+Lidar
Valley View Rd. / Tracy Ave. / Valley Ln.	Edina (Hennepin)	Tracy Ave. (SB)	Camera
W College Dr / Mississippi Pkwy-SW 4^{th} ST	Brainerd (Crow Wing)	SW 4^{th} St. (SB)	Camera+Lidar
Madison Ave / MN22	Mankato (Blue Earth)	Madison Ave. (WB)	Camera
MN95 / N Rum River Dr	Princeton (Mile Lacs)	MN95 (WB)	Camera+Lidar
Territorial St E / Lewis Ave N	Watertown (Carver)	Territorial St. (EB)	Camera

Intersection	City (County)	Data Collection Direction	Data Collection Method
70th St S / Jamaica Ave S	Cottage Grove (Washington)	70th St. S (WB)	Camera+Lidar
I35 / Rice Creek Pkwy-Thumb Rd / CR1	Arden Hills (Ramsey)	CR 1 (WB)	Camera
Gilmore Ave. / W Service Dr. / US 14 Connector	Winona (Winona)	W Service Dr. (EB)	Camera+Lidar
US 14/TH 43	Winona (Winona)	US 14 (EB)	Camera+Lidar
US61 / MN97 (North Junction)	Forest Lake (Washington)	MN 97 (WB)	Camera+Lidar
TH 22 / Adams St.	Mankato (Blue Earth)	TH 22 (NB)	Camera+Lidar
Minnehaha Ave. / Godfrey Pkwy. (Backup site for E 66th St / Portland Ave)	Minneapolis (Hennepin)	Minnehaha Pkwy (EB)	Camera

4.1 Data Collection Methods

Field evaluations were conducted in August 2023 and August 2024. All field data were collected during clear weather and off-peak traffic periods to minimize the potential impacts of confounding variables such as weather and traffic congestion.

To collect data regarding yielding behavior, high-definition video cameras were installed at each roundabout site. The camera focused on only one leg of the roundabout and captured both entry and exit. At each location, the naturalistic behavior of people walking and biking while crossing the roundabout at entry or exit was recorded. Additionally, to ensure a sufficient sample size at each site, pedestrian and bicycle crossing events were also staged by members of the MSU research team. For the staged crossing events, the following approach was utilized:

1. A pedestrian or bicyclist stood on the roadside near the crosswalk entrance and waited for a vehicle to approach the crosswalk.
2. When a vehicle approached the crossing, the pedestrian indicated their intention to cross by standing at the curb with one foot in the crosswalk while facing the oncoming traffic. In case of a bicyclist, the front wheel of the bike was put in the crosswalk to show their intention to cross. The distance of the pedestrian or bicyclist from the vehicle when they first show their intention to cross was predetermined based upon site-specific factors such as stopping sight distance.
3. The pedestrian/bicyclist would start crossing the road when the driver in the nearest lane yielded, and eye contact was maintained with the driver at all times.
4. If there were additional vehicles approaching in the subsequent lanes and the staged pedestrian or bicyclist had already entered the crosswalk, they would wait until the intention of the approaching vehicle was determined.

The procedure was repeated until a target sample size was obtained at each entrance and exit approach. At each of the sites, 100 crossing events were staged. These staged events included 50 events at entry lane and 50 events at exit lane of the roundabout. Half of the crossing events (i.e., 25 at each entry and exit lane) included a bicyclist while the other half included a pedestrian. Figure 2 shows an example of a staged crossing event. Three of the 16 sites had a rectangular rapid flashing beacon (RRFB) installed at the data collection approach. In such cases, crossing events were staged under two scenarios- 1) RRFB was activated prior to crossing, and, 2) RRFB was not activated. There were also a number of sites that had an exclusive right-turn or bypass lane. In such cases, crossing events were staged on both the exclusive right-turn lane and the adjacent through lane.

It is important to note that this study did not assess driver compliance with statutory yield laws, which in many jurisdictions, including in Minnesota, require drivers to yield only when a pedestrian is within the crosswalk. Rather, the intent was to evaluate driver yielding behavior in response to a pedestrian or bicyclist demonstrating a clear intention to cross, regardless of legal obligation. As such, a failure to yield in these staged scenarios should not be interpreted as a traffic violation but rather as an indicator of driver behavior and potential exposure risk for vulnerable road users.

Figure 2 Example of a Staged Crossing Event

The second important aspect of the data collection process was to record the speed selection behavior of the drivers as they enter the roundabout. Continuous speed profiles of vehicles entering the roundabout were collected under two scenarios- 1) when a road user (pedestrian or bicyclist) was trying to cross the roundabout, and 2) when no road user was present at the crosswalk. Speed data were collected on the upstream approach using handheld LIDAR devices, which allowed for tracking of vehicles over time and space. A team of data collectors were stationed at covert locations upstream of the crosswalk. The data collectors recorded the speed of the approaching vehicles up to the point when the vehicle reached the crosswalk. Since only one vehicle could be targeted at a time using LIDAR, the speed data were recorded for only the lead vehicles in the lane nearest to the pedestrian or bicyclist. In the case of staged pedestrian crossing events, the pedestrian and the team of speed data collectors were in contact with each other via cell phone to synchronize the vehicles they were targeting. Only free-flowing vehicles with a minimum headway of three seconds were targeted for data collection.

Chapter 5: Data Analysis

As stated earlier, field data collection was conducted at 16 roundabout locations in Minnesota. This included data collection as to whether drivers entering or exiting the roundabout yielded to persons walking or biking (also referred to as a vulnerable road user, or VRU) intending to cross, as well as the speed behavior of drivers entering the roundabout in the absence and presence of VRUs. This chapters discusses data preparation methods, presents the data summary and results of the statistical analyses.

5.1 Data Preparation

Two separate datasets were prepared for analysis purposes. This included a dataset to investigate the yielding response of drivers at roundabout entry and exits and a separate dataset to examine speed behavior on roundabout entry. The following sub-sections discuss data extraction and preparation methods for each dataset separately.

5.1.1 Yielding Behavior Dataset

During field data collection, at least 100 crossing events were staged in addition to any naturalistic crossing events. This included 50 events each at the entry and exit of the roundabout. Half of these events (i.e., 25 at each entry and exit) involved a person biking, and the other half included a person walking. Data were collected using video cameras and reviewed by experienced research team members in the laboratory. Important information related to driver behavior and the crossing event was extracted manually for each crossing event. This included the following details:

- Driver response to the crossing event (stop and yield, slow down and yield, slow down but did not yield, did not slow down)
- Type of crossing event (person walking or biking)
- Location of crossing event (roundabout entry or exit)
- Vehicle lane position (left/right/middle)
- Vehicle type (passenger car/heavy vehicle)
- Crossing direction (from curb to splitter island or vice versa, from splitter island to right-turn bypass island or vice versa)
- RRFB status (on/off/not present)
- Pedestrian behavior during naturalistic crossing events (waiting for a gap in traffic, waiting for the driver to yield, asserting their right of way (ROW))

Furthermore, for each roundabout included in the study, the following geometric and other site-specific details were collected using Google Maps and Street View and integrated with the data.

- Number of circulating lanes, width of circulating lanes (min/max)
- Number of legs
- Number and width of lanes on approach and exit

- Posted speed limit and advisory speed
- Entry and exit radius
- Distance between the crosswalk and yield line
- Inscribed circle diameter
- Type of traffic signage present at both entry and exit

Ultimately, a comprehensive dataset was prepared that included the details mentioned above. Each observation in the dataset represented one interaction between a vehicle and a VRU. A total of 2,827 vehicle-VRU interactions were observed across the 16 roundabout locations.

5.1.2 Speed Selection Dataset

Speed data for vehicles approaching a roundabout were collected using handheld lidar at 9 locations. Separate data were recorded when no VRU was present at the crosswalk and when a VRU was waiting to cross. The speed data for baseline scenario, i.e., when no VRU is present at the crosswalk, could not be collected at one of the sites (US 14 and TH 43) due to excessive traffic volume resulting in consistent queuing at roundabout entry. Thus, speed data for this scenario was available for 8 sites as opposed to 9 sites for scenario when VRU is present.

In each case, speed profiles of 40-50 vehicles were recorded at each site. The raw lidar collected at the site included timestamps, distances, and speeds for each tracked vehicle. These data were reduced to get speed profiles of vehicles. A limitation of lidar data is that it is not possible to measure the speed of every vehicle at the same point in space. Thus, the speed profiles were interpolated to fill gaps. Ultimately, this resulted in spot speed measurements of vehicles at every 1 ft. Since the primary objective was to investigate speed differences in the presence and absence of a pedestrian or bicyclist at the roundabout crosswalk, speed measurements were only recorded up to the crosswalk. Figure 3 shows an example of raw speed profiles collected using lidar and subsequent interpolated speed profiles at every 50 ft. The roundabout crosswalk was considered the reference point for all analysis purposes.

The spot speed measurement data was also integrated with site-specific features and roundabout geometry characteristics extracted for the yielding behavior dataset. Ultimately, each observation in the dataset represented a spot-speed measurement of a vehicle at a certain distance from the crosswalk. The spot speed measurements were interpolated for every foot for subsequent statistical analysis.

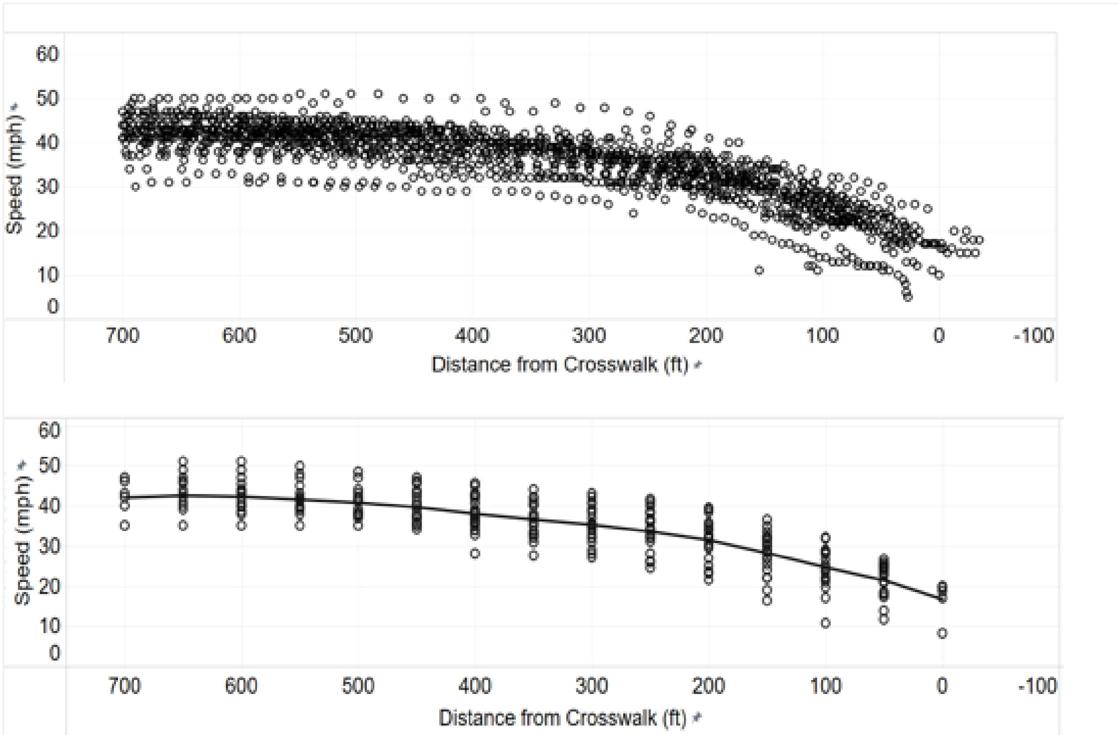

Figure 3 Raw and Interpolated Speed Profiles of Vehicles Approaching the Roundabout Crosswalk

5.2 Data Summary

The yield rates were initially assessed for each site separately. Table 4 provides summary information detailing the yielding rates at both roundabout entry and exit for each site. Most sites showed yielding rates on roundabout entry exceeding 80%, with a few exceptions. In contrast, yield rates on the exit leg were significantly lower. One of the sites, namely Minnehaha Ave./Godfrey Pkwy, consistently showed higher yield rates at entry and exit. This was primarily because of its unique location. The site was located within Minnehaha Regional Park, a popular local tourist spot with relatively higher natural pedestrian and bicycle activity. The roundabout also has a posted speed limit of 20 mph.

Sites were also grouped based on their characteristics. Yield rates towards VRU were relatively similar at roundabout entry. On exits, yield rates were lower for person biking compared to person walking. Similarly, the crossing direction did not show any meaningful differences in yield rates on entry. However, yield rates on exits were markedly higher when the crossing event occurred to or from a right-turn bypass island. Interestingly, RRFB presence did not show a substantive impact on yield rates at the aggregate level, particularly on entry. At roundabout exits, yield rates were slightly better on sites with RRFB, irrespective of whether it was activated before the crossing event. Yield rates were also higher among vehicles in the near lane (lane near to VRU) compared to the vehicles in the far lanes. This trend was markedly more pronounced on exits, where only 9% of vehicles in the far lane yielded.

The behavior of the vehicle in the adjacent lane also influenced the behavior of the subject vehicle. For example, if the driver in the adjacent lane yielded, then the subject driver also yielded in 91% of the cases on entry and in 52% of the events on exits. In comparison, if the adjacent driver did not yield, the subject driver yielded only 54% and 5% of the time on entry and exit, respectively.

Double-lane roundabouts exhibited lower yielding rates (~54%) than single-lane roundabouts (75%). On exits, the yield rates were 29% and 62% on double-lane and single-lane roundabouts, respectively. Other site-specific factors also impacted yield rates. Sites with higher posted speed limits on the approaches generally showed lower yield rates. Yield rates were slightly higher in right-turn bypass lanes separated by an island (65%) than through lanes (57%).

Table 5 presents summaries of yield rates based on various site-specific factors. It should be noted that the yield rates are presented separately for entry and exit legs. The combined yield rates can be calculated using the weighted average of yield rates on entry and exit.

The yield rates among the staged and natural crossing datasets were similar. The behavior of person walking or biking during the natural crossing events was also recorded. Among the 47 pedestrian/bicyclist interactions with vehicles at entry, 68% waited for the driver to yield, while 23% asserted their right of way (ROW) by entering the crosswalk and forcing the driver to yield. Only 9% of people walking or biking waited for the traffic to clear to get a sufficient gap to cross the roundabout. Similar trends were observed on the exit leg. Nearly 77% of people walking or biking waited for drivers to yield, and 22% asserted their ROW.

Table 4 Yielding Behavior at Roundabouts by Site

Site	Type	Roundabout Entry		Roundabout Exit	
		Sample Size	Yielded	Sample Size	Yielded
4th St. / E College Dr.	Double lane	81	53%	91	45%
66th St. / Nicollet Ave.	Double lane	95	75%	101	57%
TH 316 (Red Wing Blvd.) / Tuttle Dr.	Single lane	72	92%	54	70%
US 61-US 10/Jamaica Ave S/W Point Douglas Rd S	Double lane	74	70%	38	13%
Valley View Rd./Tracy Ave./Valley Ln.	Single lane	65	91%	63	78%
W College Dr/Mississippi Pkwy-SW 4th St	Double lane	81	84%	76	37%
Madison Ave / TH 22	Double lane	71	82%	101	15%
TH 95 / N Rum River Dr	Single lane	92	79%	92	47%
Territorial St E / Lewis Ave N	Single lane	60	88%	89	56%
70th St S / Jamaica Ave S	Double lane	66	86%	67	57%
I 35 / Rice Creek Pkwy-Thumb Rd / CR1	Single lane	51	92%	67	48%
Gilmore Ave. / W Service Dr. / US 14 Connector	Single lane	87	80%	39	49%
US 14/TH 43	Double lane	95	88%	103	17%

Site	Type	Roundabout Entry		Roundabout Exit	
		Sample Size	Yielded	Sample Size	Yielded
US 61 / TH 97 (North Junction)	Double lane	141	86%	183	55%
TH 22 / Adams St.	Double lane	98	84%	333	4%
Minnehaha Ave. / Godfrey Pkwy.	Single lane	46	91%	55	98%

Yield rates towards VRU were relatively similar at roundabout entry. On exits, yield rates were lower for person biking compared to person walking. Similarly, the crossing direction did not show any meaningful differences in yield rates on entry. However, yield rates on exits were markedly higher when the crossing event occurred to or from a right-turn bypass island. Interestingly, RRFB presence did not show a substantive impact on yield rates at the aggregate level, particularly on entry. At roundabout exits, yield rates were slightly better on sites with RRFB, irrespective of whether it was activated before the crossing event. Yield rates were also higher among vehicles in the near lane (lane near to VRU) compared to the vehicles in the far lanes. This trend was markedly more pronounced on exits, where only 9% of vehicles in the far lane yielded.

The behavior of the vehicle in the adjacent lane also influenced the behavior of the subject vehicle. For example, if the driver in the adjacent lane yielded, then the subject driver also yielded in 91% of the cases on entry and in 52% of the events on exits. In comparison, if the adjacent driver did not yield, the subject driver yielded only 54% and 5% of the time on entry and exit, respectively.

Double-lane roundabouts exhibited lower yielding rates (~54%) than single-lane roundabouts (75%). On exits, the yield rates were 29% and 62% on double-lane and single-lane roundabouts, respectively. Other site-specific factors also impacted yield rates. Sites with higher posted speed limits on the approaches generally showed lower yield rates. Yield rates were slightly higher in right-turn bypass lanes separated by an island (65%) than through lanes (57%).

Table 5 Summary of Yield Rates between Entry and Exit Approaches based on Various Factors of Interest

Factor	Roundabout Entry		Roundabout Exit	
	Sample Size	Subject Vehicle Yielded	Sample Size	Subject Vehicle Yielded
Dataset				
Natural crossings	47	91%	68	41%
Staged crossings	1228	82%	1484	39%
VRU Behavior during Natural Crossing Events				
Wait for gap in traffic stream	4 (9%)	na	1 (1%)	na
Wait for driver to yield	32 (68%)	na	52 (77%)	na
Assert their ROW	11 (23%)	na	15 (22%)	na
Type of VRU				
Person walking	644	83%	651	49%
Person biking	541	81%	776	29%
Person walking with bike	90	83%	125	47%

Factor	Roundabout Entry		Roundabout Exit	
	Sample Size	Subject Vehicle Yielded	Sample Size	Subject Vehicle Yielded
Crossing Direction				
Curb to island (splitter or bypass)	620	83%	741	39%
Island (splitter or bypass) to curb	457	81%	726	36%
Right-turn bypass island to splitter island or vice versa	198	83%	82	63%
RRFB Status				
Not present	1020	82%	1285	37%
Present but off	99	84%	99	55%
Present and on	156	84%	168	42%
Lane Position wrt Pedestrian				
Far	335	69%	345	9%
Near	826	88%	1105	47%
Right-turn bypass lane (always near)	114	79%	102	49%
Response of Vehicle in Adjacent Lane				
No vehicle in adjacent lane	1175	82%	1361	43%
Vehicle in adjacent lane did not yield	24	54%	166	5%
Vehicle in adjacent lane yielded	76	91%	25	52%
Roundabout Type				
Single lane	486	87%	471	62%
Double lane	789	79%	1081	29%

Table 6 provides the descriptive statistics of the pertinent variables in the yielding behavior dataset. Separate statistics are provided for the roundabout entry and exit crossing scenarios. It should be noted that the VRU can interact with multiple vehicles during each crossing event. For example, on a roundabout with multiple approach lanes, multiple vehicles could approach the roundabout crossing at the same time. Similarly, in situations where a queue of vehicles approaches a roundabout, the interaction of each vehicle with the VRU is recorded until one of the vehicles in the queue yields. Thus, the sample size in Table 6 represents the number of vehicle-pedestrian or vehicle-bicyclist interactions across all sites. Overall, the yield rates were 82% and 39% on roundabout entry and exit, respectively, across all sites combined.

Table 6 Descriptive Statistics of Pertinent Variables for Yielding Behavior Dataset

Parameter	Roundabout Entry				Roundabout Exit			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Type of VRU								
Person walking	0.00	1.00	0.51	0.50	0.00	1.00	0.42	0.49
Person biking	0.00	1.00	0.42	0.49	0.00	1.00	0.50	0.50
Person walking with bike	0.00	1.00	0.07	0.26	0.00	1.00	0.08	0.27
Crossing direction								

Parameter	Roundabout Entry				Roundabout Exit			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Splitter island to right-turn bypass lane or vice versa	0.00	1.00	0.16	0.36	0.00	1.00	0.05	0.23
Island (splitter or bypass) to curb	0.00	1.00	0.32	0.47	0.00	1.00	0.45	0.50
Curb to island (splitter or bypass)	0.00	1.00	0.44	0.50	0.00	1.00	0.43	0.50
RRFB								
Present – on	0.00	1.00	0.12	0.33	0.00	1.00	0.11	0.31
Present – off	0.00	1.00	0.08	0.27	0.00	1.00	0.06	0.24
Not present	0.00	1.00	0.80	0.40	0.00	1.00	0.83	0.38
Vehicle lane position								
Near	0.00	1.00	0.74	0.44	0.00	1.00	0.78	0.42
Far	0.00	1.00	0.26	0.44	0.00	1.00	0.22	0.42
Number of travel lanes								
2	0.00	1.00	0.50	0.50	0.00	1.00	0.80	0.40
1	0.00	1.00	0.50	0.50	0.00	1.00	0.20	0.40
Approach legs								
5	0.00	1.00	0.10	0.45	0.00	1.00	0.07	0.25
4	0.00	1.00	0.72	0.52	0.00	1.00	0.81	0.39
3	0.00	1.00	0.18	0.39	0.00	1.00	0.12	0.33
Roundabout type								
Single lane	0.00	1.00	0.38	0.49	0.00	1.00	0.30	0.46
Double lane	0.00	1.00	0.62	0.49	0.00	1.00	0.70	0.46
Min circulating lane width (ft)	11.90	25.40	16.93	3.91	11.90	25.40	17.18	3.62
Max circulating lane width (ft)	12.89	30.19	22.51	5.79	12.89	30.19	23.63	5.36
Entry radius (ft)	36.80	183.15	105.33	36.76	36.80	183.15	114.72	37.02
Exit radius (ft)	36.80	113.00	81.16	22.93	36.80	113.00	84.56	18.79
Crosswalk Width (ft)	9.00	33.15	21.22	6.39	9.00	33.15	18.86	5.62
Lane Width (ft)	9.00	18.10	11.89	1.62	9.00	18.10	12.97	3.10
Distance between crosswalk and yield line (ft)	23.30	87.90	45.24	15.30	23.30	87.90	45.67	13.35
AADT (veh/day)	3,750	21,431	10,355	5,883	3,750	21,431	12,167	6,757
Speed limit (mph)	20	65	41.45	12.15	20	65	41.84	10.88
Inscribed circle diameter (ft)	94.16	229.85	174.59	40.46	94.16	229.85	183.66	37.24
Ped crossing sign R1-6a	0.00	1.00	0.34	0.47	0.00	1.00	0.45	0.50
Ped Crossing Sign W11-2	0.00	1.00	0.56	0.50	0.00	1.00	0.92	0.28
Vehicle yielded	0.00	1.00	0.82	0.38	0.00	1.00	0.39	0.49
Sample size	1,275 vehicle-VRU interactions				1,552 vehicle-VRU interactions			

Table 7 presents a similar descriptive statistic table for the speed selection analysis dataset for two scenarios. First, when a VRU was at the crosswalk waiting to cross the roundabout, and second, when no VRU was at the roundabout crossing. Figure 4 shows the speed profiles obtained from lidar for the roundabout located on the TH95 / N Rum River Dr. Again, separate speed profiles are shown for vehicles that interacted with VRU at roundabout entry and vehicles that did not. When a VRU was present, the profiles were further divided based on the driver's response- whether the driver yielded to the VRU. The figure shows differences in speed selection behavior based on the presence of a pedestrian. Drivers who yielded to pedestrians or bicyclists showed consistently lower speeds than drivers who did not, although other site-specific factors may also influence this trend. The site-by-site speed profiles are presented in the Appendix-B of this report.

Table 7 Descriptive Statistics of Pertinent Variables for Speed Selection Dataset

Parameter	VRU Present				VRU Not Present			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Type of VRU								
Person walking	0.00	1.00	0.53	0.50	na	na	na	na
Person biking	0.00	1.00	0.47	0.50	na	na	na	na
Yield to VRU	0.00	1.00	0.79	0.41	na	na	na	na
Speed (mph)	5.00	64.00	35.07	9.92	5.00	58.00	36.21	8.75
Heavy vehicle	0.00	1.00	0.04	0.20	0.00	1.00	0.09	0.29
RRFB present	0.00	1.00	0.12	0.33	na	na	na	na
Vehicle lane position								
Right	0.00	1.00	0.56	0.50	0.00	1.00	0.50	0.50
Left	0.00	1.00	0.34	0.47	0.00	1.00	0.49	0.50
Right-turn bypass lane	0.00	1.00	0.10	0.29	0.00	1.00	0.01	0.08
Number of travel lanes								
2	0.00	1.00	0.62	0.50	0.00	1.00	0.20	0.40
1	0.00	1.00	0.38	0.49	0.00	1.00	0.80	0.40
Approach legs								
5	0.00	1.00	0.07	0.26	0.00	1.00	0.10	0.29
4	0.00	1.00	0.81	0.39	0.00	1.00	0.81	0.39
3	0.00	1.00	0.12	0.32	0.00	1.00	0.09	0.29
Type								
Single lane	0.00	1.00	0.38	0.49	0.00	1.00	0.31	0.46
Double lane	0.00	1.00	0.62	0.49	0.00	1.00	0.69	0.46
Min circulating lane width (ft)	11.90	25.40	15.70	4.07	11.90	17.50	14.50	2.02
Max circulating lane width (ft)	12.89	30.19	21.46	6.16	12.89	30.19	22.60	6.36
Entry radius (ft)	52.40	183.15	104.16	44.56	52.40	183.15	109.93	49.52
Exit radius (ft)	36.80	113.00	75.51	24.75	36.80	113.00	69.66	19.92
Crosswalk Width (ft)	12.35	33.15	20.72	6.97	12.35	33.15	19.37	6.56
Lane Width (ft)	10.00	19.00	13.45	3.20	10.00	19.00	13.12	2.95

Parameter	VRU Present				VRU Not Present			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Distance from crosswalk (ft)	0.00	984.00	401.59	217.07	0.00	1001.00	420.11	222.15
AADT (veh/day)	6200.0	22000.0	11080.0	4780.0	3750.00	21431.00	10422.82	6449.73
Speed limit (mph)	30.00	65.00	45.35	10.34	30.00	65.00	46.34	9.72
Inscribed circle diameter (ft)	94.16	229.85	167.98	44.07	94.16	229.85	171.77	46.73
Ped crossing sign R1-6a	0.00	1.00	0.35	0.48	0.00	1.00	0.54	0.50
Ped Crossing Sign W11-2	0.00	1.00	0.49	0.50	0.00	1.00	0.24	0.43
Sample size	324,823 speed measurements across nine sites				253,954 speed measurements across eight sites			

Note: na = not applicable

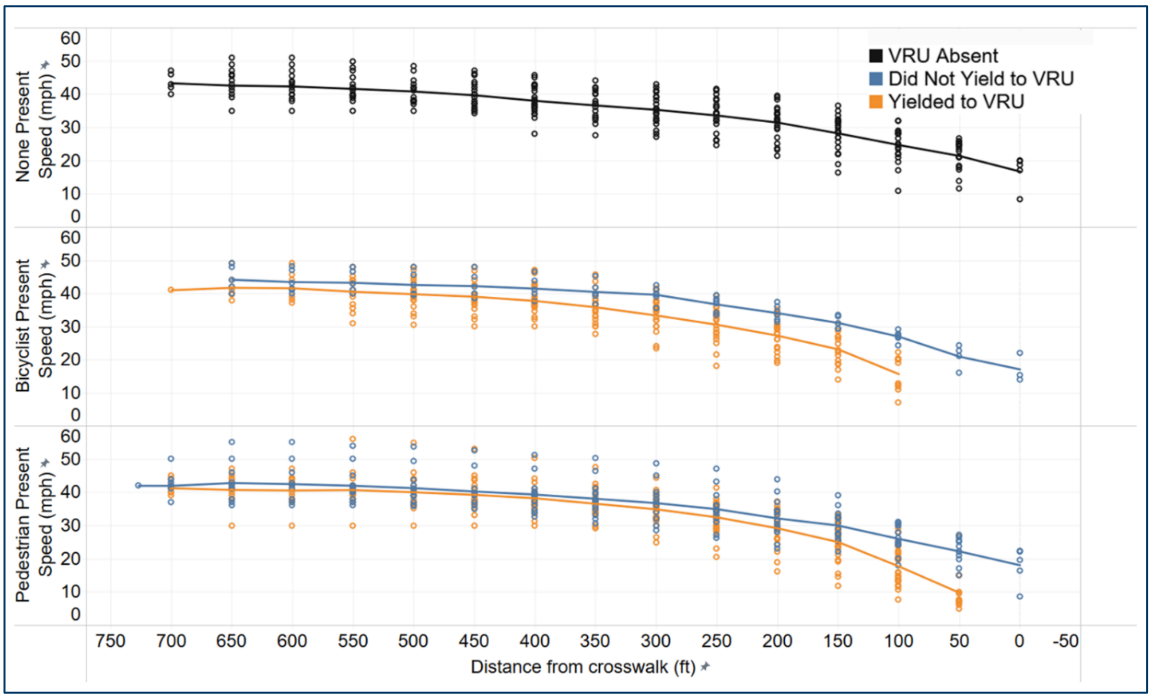

Figure 4 Speed Profile of Vehicles Approaching Roundabout Crossing at Entry Leg (TH95 / N Rum River Dr)

5.3 Statistical Methods

Ultimately, various factors may impact both driver-yielding behavior and speed selection. This includes the presence/absence of persons walking or biking and geometric and traffic characteristics associated with the site. Consequently, analyses of these data are well suited for various types of regression analyses.

To model the yielding behavior of drivers, logistic regression models were estimated to identify factors associated with the likelihood of a driver yielding to persons walking or biking. A binary indicator variable was defined which was equal to one in cases where the driver yields to the VRU and zero otherwise. The model takes the form as shown in Equation 1.

$$Y_{ijk} = logit(P_{ijk}) = ln\left(\frac{P_{ijk}}{1-P_{ijk}}\right) = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_m X_m, \quad (1)$$

where P_{ijk} is the probability of k^{th} vehicle yielding during the i^{th} crossing event at site j, X_1 to X_m are a series of predictor variables associated with yielding behavior and β_1 to β_k are a series of estimable parameters. Since multiple crossing events were staged at each site with each crossing event resulting in one or more interactions with a vehicle, a random effects modeling framework is adopted to account for correlation among observations due to unobserved site-specific and event-specific characteristics by re-writing the constant term in Equation 1 as follows:

$$\beta_{0j} = \beta_0 + \omega_{0j} + \omega_{1i(j)}, \quad (2)$$

where ω_{0j} is a randomly distributed random effect for site j, $\omega_{1i(j)}$ is a nested random effect for i^{th} crossing event within site j, all other variables are as previously defined.

Additionally, a series of random effects multiple linear regression models were estimated to understand the speed selection behavior of drivers entering roundabouts in the presence and absence of VRU. The general form of the model is shown in Equation 3.

$$Y_{ijk} = \beta X_{ijk} + u_{0j} + u_{1i(j)} + \varepsilon_{ijk}, \quad (3)$$

where Y_{ijk} is the speed of vehicle i at site j at a distance k upstream of the crosswalk, X_{ijk} is a vector of predictor variables that are associated with speed selection, β is a vector of estimable parameters, and ε_{ijk} is the traditional idiosyncratic error term. The term u_{oj} is a random effect that accounts for unobserved site-specific effects, and the term $u_{1i(j)}$ is a nested random effect for vehicle i within site j.

5.4 Results and Discussion

The following sub-sections present and discuss the results from statistical analyses separately for both yielding behavior and speed selection behavior.

5.4.1 Yielding Behavior

Three separate analyses were conducted to evaluate driver yielding behavior. This included separate regression models for interactions that occurred at (1) the roundabout entry and (2) the roundabout exit, as well as (3) a combined dataset for all events. Table 8 presents the results for all three analyses. The table presents the parameter estimates for each variable of interest and standard errors in parenthesis. An asterisk indicates those parameters that were statistically significant at 95% confidence. When interpreting the results, a positive coefficient indicates that drivers are more likely to yield as that variable increases, while the opposite is true for a negative coefficient. For the distance-related variables (i.e., lane width and distance between crosswalk and roundabout), these parameters are reflective of the impacts of a one-ft increase in width on the likelihood of yielding. In contrast, the other variables are all categorical in nature. In these cases, the parameters reflect the difference in yielding rates between that specific category and the referenced baseline category of interest (e.g., yielding rates for persons biking or walking their bike across the crosswalk are shown to be lower than the yielding rates for the baseline scenario where a pedestrian is crossing without a bike). To aid in interpreting and visualizing the results, Figure 5 presents the odds ratio for each parameter estimate and its 95% confidence interval. These odds ratios correspond to the change in the odds of a driver yielding for either a one-unit increase in the parameter (in the case of continuous variables) or the change in odds of yielding for a specific category as compared to a baseline category.

First, there was a significant difference in yielding rates based on the type of VRU with which the driver interacted. Interestingly, drivers were more likely to yield to persons walking compared to persons biking. Among people biking, events where the person walked with the bike instead of riding showed a higher likelihood of driver yielding. This may reflect challenges in motorists' scanning behavior, particularly when the non-motorized users are moving at higher speeds. For example, as bicyclists are generally moving at higher speeds, it may be more challenging for drivers to effectively identify them. Interestingly, people who walked their bike across the crosswalk showed marginally higher (but not statistically significant) yielding rates on the entry approach. Further research is necessary to understand whether this is reflective of differences in driver scanning behavior, to drivers' expectations as to the behavior of those walking versus biking, or some other factors.

When considering crossing direction and type of leg, yield rates were significantly lower at exits compared to entry regardless of crossing direction. One potential reason for this trend is the higher speeds of exiting vehicles and lower willingness to stop when exiting so as not to impede traffic within the roundabout.

Drivers yielded to VRU much more frequently when crossing from an island (splitter or bypass). This was true when crossing from splitter island to curb and from right-turn bypass island to splitter island (or vice versa). On entry, the odds of driver yielding were twice as high when crossing from splitter island compared to when crossing from the curb. On exit, the odds of yielding were 1.7 times higher when crossing event initiated from the splitter island compared to the curb. When a pedestrian is at the splitter island, drivers may perceive them as already engaged in crossing rather than just waiting, increasing the likelihood of driver yielding. Moreover, drivers may consider the pedestrian at the splitter island as the pedestrian being present within the roadway, thus yielding due to the legal requirement. Related to this point, vehicles in the lane near the VRU intending to cross were more likely to yield on both entry and exit. More specifically, the odds of yielding reduced by 63-73 percent when the driver was in the far lane compared to the near lane. This again may be due to, in part, higher visibility of VRU waiting at crossing to vehicles in the near lane.

The presence and status of RRFB on yielding behavior were also investigated. Overall, yield rates were generally higher when the intention to cross was accompanied by the activation of the RRFB. For example, on exits, the odds of yielding were 2.6 times on sites with RRFB compared to sites without RRFB. Interestingly, those sites that included RRFBs tended to show higher yielding rates even when the device was not activated. It is unclear whether this is reflective of an impact of the device (irrespective of whether it is activated) or to some inherent differences between the sites with RRFBs versus those without.

When the data were examined separately for entering and existing traffic, yield rates were higher on the entry approaches when the device was active. However, this result was not statistically significant. In contrast, yield rates were higher among exiting traffic for both the active and inactive RRFB scenarios (as compared to the absence of an RRFB altogether). This may be reflective of driver scanning behavior as they prepare to exit the roundabout.

At roundabout sites with multiple travel lanes, if vehicles in each travel lane approach the crosswalk simultaneously, one vehicle's behavior may influence the behavior of the vehicle in the adjacent lane. Thus, in situations where vehicles in adjacent lanes arrived at the crosswalk simultaneously or in a shorter time gap before the VRU actually entered the crosswalk, the effect of the behavior of the driver in the adjacent lane on the subject vehicle was also investigated. The analysis results showed that the yielding behavior of the subject vehicle closely followed the response of the vehicle to VRU in the adjacent lane. If the vehicle in the adjacent yielded, the subject vehicle was also highly likely to yield. If the driver in the adjacent lane did not yield, the subject vehicle was also less likely to yield.

Table 8 Random Effects Logistic Regression Model Results for Yielding Behavior

Parameter	Estimate (standard error)		
	Combined Data	**Entry Only**	**Exit Only**
Intercept	5.04 (0.64)*	4.21 (1.11)*	3.45 (0.86)*
Type of VRU			
Pedestrian	*Baseline*	*Baseline*	*Baseline*
Riding bike	-0.44 (0.12)*	-0.16 (0.17)	-0.68 (0.17)*
Walking with bike	-0.05 (0.20)	0.31 (0.36)	-0.33 (0.25)
Crossing direction × Type of leg			
Curb to island (splitter or bypass) on entry	*Baseline*	*Baseline*	na
Island (splitter or bypass) to curb on entry	0.78 (0.20)*	0.72 (0.20)*	na
Right-turn bypass island to splitter island on entry or vice-versa	1.42 (0.30)*	1.18 (0.31)*	na
Curb to island (splitter or bypass) on exit	-2.22 (0.19)*	na	*Baseline*
Island (splitter or bypass) to curb on exit	-1.79 (0.19)*	na	0.54 (0.17)*
Right-turn bypass island to splitter island on exit or vice versa	-1.01 (0.36)*	na	1.80 (0.56)*
RRFB			
Not present	*Baseline*	*Baseline*	*Baseline*
Present but off	0.52 (0.29)	0.25 (0.36)	0.95 (0.48)*
Present and on	0.62 (0.27)*	0.60 (0.33)	0.95 (0.48)*

Parameter	Estimate (standard error)		
	Combined Data	Entry Only	Exit Only
Vehicle lane position with respect to VRU			
Near lane	*Baseline*	*Baseline*	*Baseline*
Far lane	-1.06 (0.18)*	-1.00 (0.24)*	-1.31 (0.30)*
Driver behavior in adjacent lane			
Not present	*Baseline*	*Baseline*	*Baseline*
Present but did not yield	-0.86 (0.34)*	-1.12 (0.52)*	-0.54 (0.44)
Present and yielded	1.28 (0.35)*	0.99 (0.44)*	1.58 (0.57)*
Number of travel lanes (excluding right-turn bypass lane) × Roundabout type			
Single lane roundabout with 1 travel lane	*Baseline*	*Baseline*	*Baseline*
Single lane roundabout with 2 travel lanes	-1.04 (0.40)*	0.06 (0.67)	-1.80 (0.96)
Double lane with 1 travel lanes	-1.26 (0.23)*	-0.44 (0.42)	-1.50 (0.33)*
Double lane with 2 travel lanes	-1.42 (0.27)*	-0.80 (0.37)*	-2.03 (0.50)*
Lane width (ft)	-0.25 (0.04)*	-0.16 (0.08)*	-0.26 (0.06)*
Distance between crosswalk and roundabout (ft)	0.01 (0.01)*	-0.01 (0.01)	0.02 (0.01)
Vehicle exiting via			
Right turn	na	na	*Baseline*
Thru or left turn	na	na	-0.48 (0.23)*
Random effects	Standard deviation	Standard deviation	Standard deviation
Site ID	0.29	0.58	0.71
Crossing event ID (nested within site)	0.65	0.22	0.39

Note: * = estimate is statistically significant at 95% confidence interval; na = not applicable

The impact of several site geometry characteristics on yield rates was also investigated. The results showed that yield rates were significantly lower on double-lane roundabouts compared to single-lane roundabouts on both entry and exit (odds of yielding on double lane roundabouts were 72-76% lower than on single lane roundabouts). Moreover, as the number of travel lanes (excluding bypass lanes) increased, drivers were less likely to yield to VRUs. This supports prior research that has shown yield rates to decrease as the complexity of navigation increases (Arnold et al., 2013; Hourdos et al., 2012). The width of the lane also impacted yield rates. Yield rates were found to decrease as the width of the lane increased. For every one-foot reduction in lane width, the odds of yielding reduced by 15-23%. The distance between the crosswalk and the roundabout yield line was also included in the analysis. The results showed that overall yield rates increased as the distance increased. However, this parameter did not show any meaningful impact of yield rates separately on roundabout entry and exit.

Additional factors, such as traffic volume and roundabout geometric characteristics (e.g., inscribed diameter, entry radii), were also considered. However, many of these geometric characteristics are inherently correlated with other characteristics, most notably the approach speed limits and the number of circulating lanes. Consequently, it was not possible to discern potential impacts of some of these factors. Finally, data collection was primarily conducted during off-peak hours to minimize the potential impacts of congestion on the analysis (i.e., lower speeds or higher yielding rates). At these lower volume levels, no significant differences were observed across sites with different volumes during the study period.

Lastly, the path that the vehicles followed to exit the roundabout was also considered when investigating yield rates. Vehicles that made a right turn to exit the roundabout at their first opportunity were significantly more likely to yield than vehicles that utilized the roundabout for a through movement or a left (3/4) turn. These right-turning drivers may be more cognizant of adjacent non-motorized traffic, or this higher yielding rate may be a function of lower entry speeds as compared to vehicles who proceed through to a subsequent exit.

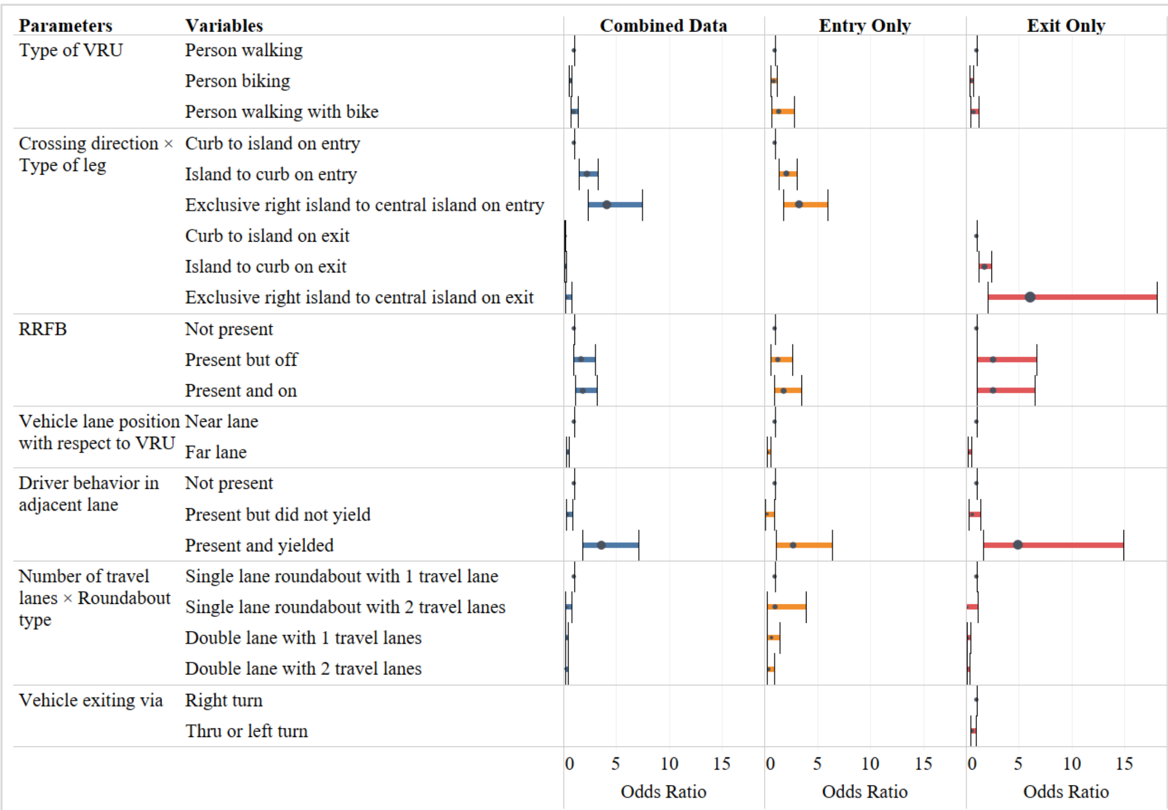

Figure 5 Odds Ratio for Yielding Behavior

5.4.2 Speed Selection Behavior

Three separate models were estimated to analyze vehicle speed profiles as drivers approached the crosswalk on roundabout entry: (1) one model for vehicles that yielded to a VRU who was present at the crosswalk; (2) a second model for vehicles that did not yield to a VRU; and (3) a final model for vehicles that approached in the absence of a VRU. Table 9 presents the models for speed selection behavior under these three scenarios. The table presents the estimated coefficients and standard errors in parentheses. The significant estimates at 95% confidence are marked with an asterisk. Variables not included in any of the three models are marked as not applicable (na) where appropriate. Indicator variables were created for several variables, including the distance of vehicles from the roundabout pedestrian crosswalk.

The model results showed that the vehicle speeds were consistently higher for passenger cars compared to heavy vehicles when approaching the roundabout crosswalk. Surprisingly, average speeds of heavy vehicles were 3.3 mph lower than passenger cars when the vehicles yielded to VRU and 4.6 mph lower when they did not. The type of VRU present at the crosswalk also showed a marginal effect on vehicle speeds. Speeds were marginally higher when person with bike were at the crosswalk compared to person walking. This may be due to the perception that persons walking are more vulnerable than persons biking, making drivers more risk-averse towards pedestrians, resulting in reduced travel speed.

Turning to site characteristics, the speed of vehicles while traveling in the right-turn bypass lane was also consistently higher than in the through lanes. Some sites where speed data were collected had another roundabout located upstream, influencing vehicle speeds. An indicator variable that explicitly captured this effect was included in the model. On such sites, average speeds were 2.8 to 3.9 mph lower than similar sites without an upstream roundabout.

The primary variable of interest in these analyses was the vehicle's distance from the roundabout crosswalk, which was used to capture the spatial trends in driver speeds as they approached the roundabout crosswalk. The distance of the vehicle from the roundabout crosswalk was grouped into 50-foot intervals. Given that the speed limits would also influence these speeds, interaction terms were included for each speed limit and distance band combination to capture potential differences in speed profiles across speed zones. The combination of a 30-mph speed limit and a distance greater than 650 ft from the crosswalk was specified as the baseline category in the regression model. Accordingly, all estimated coefficients represent deviations in mean vehicle speed relative to this baseline condition.

At 30 mph sites, the results showed that the drivers began reducing their speeds about 300 ft upstream of the roundabout crosswalk when VRUs were present. The drivers that yielded to the VRU showed an average rate of speed reduction of 3.9 mph for every 50 ft traveled between 300 ft and the crosswalk. The speed reductions become progressively larger in each downstream band, reaching up to 25 mph in the final 50 feet before the crosswalk. In contrast, the drivers that did not yield to the VRU maintained higher speeds until much closer to the crosswalk and exhibited less rapid deceleration. More specifically, the average speed reduction was only 18 mph over the 700-foot approach among non-yielding drivers compared to 25 mph among yielding drivers.

At sites posted at 45-mph speed limits, the approach speeds of the drivers were significantly higher, with average speeds at more than 650 ft from the crosswalk being 10-12 mph above than at 30-mph sites. As in the 30-mph case, vehicles that yielded to VRUs began reducing their speeds earlier than those that did not. For drivers that yielded, meaningful speed reductions started nearly 500 feet upstream of the crosswalk, with an average deceleration of 5 mph per 50 feet. Non-yielding drivers showed slightly delayed braking and lower deceleration with an average speed reduction rate of 2.3 mph per 50 feet. The total reduction in speed on the roundabout approach was 34 mph among drivers who yielded to VRU compared to only a 26-mph reduction among non-yielding drivers.

Sites posted at speed limits more than 45 mph exhibited the highest upstream speeds, averaging 16-17 mph above those at 30 mph sites. However, even at these higher-speed sites, yielding behavior was associated with early and substantial speed reductions. Drivers who yielded began decelerating as early as 700 feet upstream of the crosswalk, with an average speed reduction of 2.8 mph per 50 feet. The overall speed reduction was about 41 mph over the approach that extended more than 850 ft. Drivers who did not yield also reduced their speeds over the same approach distance, though the rate and magnitude of deceleration were less pronounced than for yielding drivers. The overall speed reduction was about 33 mph and exhibited an average speed reduction of 2.2 mph per 50 feet.

Overall, this indicates that vehicles that did not yield also tended to have higher approach speeds. This is consistent with prior research that has shown an inverse relationship between motor vehicle speed and yield rates (48, 49).

In scenarios where no VRU was present at the crosswalk, approach speeds were consistently higher across all speed zones and showed more gradual deceleration patterns. At 30-mph sites, drivers began braking approximately 200-250 ft upstream of the crosswalk, with the speed reduction rate being 2.4 mph per 50 ft within the 250-ft approach to the crosswalk. Similar trends were observed at higher speed limit locations where both the overall reduction in speeds and the rate of speed reduction were significantly lower compared to scenarios when a VRU was present. This suggests that drivers tend to maintain higher speeds when there is no perceived need to yield, further reinforcing the influence of pedestrian presence on driver behavior.

Table 9 Random Effects Multiple Linear Regression Model for Speed Selection Behavior

Parameter	Estimate (standard error)		
	Yielded to VRU	**Did Not Yield to VRU**	**VRU Not Present**
Intercept	31.83 (1.43)*	33.87 (1.39)*	31.80 (1.95)*
Vehicle type			
Passenger car	*Baseline*	*Baseline*	*Baseline*
Heavy vehicle	-3.33 (0.88)*	-4.57 (2.43)*	-3.29 (0.64)*
Type of VRU			
Person walking	*Baseline*	*Baseline*	*Baseline*
Person biking	0.69 (0.384)	0.40 (0.85)	na
Unique site features (1 if yes, 0 otherwise)			
Travel on right-turn bypass lane	3.74 (0.07)*	3.54 (0.10)*	0.75 (0.07)*
Presence of roundabout upstream	-2.82 (2.13)	-3.94 (2.08)	-3.54 (3.12)
Speed limit and distance from crosswalk			
30 mph – 651+ ft	*Baseline*	*Baseline*	*Baseline*
30 mph – 601–650 ft	0.36 (0.19)*	-0.20 (0.19)	0.65 (0.104)*
30 mph – 551–600 ft	0.46 (0.12)*	-0.37 (0.19)*	1.36 (0.10)*
30 mph – 501–550 ft	0.45 (0.12)*	-0.41 (0.19)*	1.61 (0.09)*
30 mph – 451–500 ft	0.35 (0.12)*	-0.54 (0.19)*	1.57 (0.09)*
30 mph – 401–450 ft	0.10 (0.12)	-0.64 (0.19)*	1.34 (0.09)*
30 mph – 351–400 ft	-0.27 (0.16)*	-1.07 (0.19)*	0.88 (0.09)*

Parameter	Estimate (standard error)		
	Yielded to VRU	Did Not Yield to VRU	VRU Not Present
30 mph – 301–350 ft	-0.81 (0.16)*	-1.72 (0.19)*	0.17 (0.09)
30 mph – 251–300 ft	-1.53 (0.16)*	-2.62 (0.19)*	-0.76 (0.09)*
30 mph – 201–250 ft	-2.79 (0.16)*	-4.25 (0.19)*	-2.41 (0.09)*
30 mph – 151–200 ft	-4.79 (-0.16)*	-6.24 (0.19)*	-4.09 (0.09)*
30 mph – 101–150 ft	-9.095 (0.16)*	-9.04 (0.19)*	-5.85 (0.09)*
30 mph – 51–100 ft	-16.96 (0.12)*	-13.03 (0.19)*	-8.50 (0.09)*
30 mph – 0–50 ft	-24.91 (0.15)*	-17.71 (0.20)*	-14.53 (0.09)*
45 mph – 851+ ft	11.77 (2.13)*	10.96 (2.02)*	12.15 (2.96)*
45 mph – 801–850 ft	11.83 (2.13)*	10.65 (2.02)*	12.18 (2.95)*
45 mph – 751–800 ft	11.61 (2.13)*	10.47 (2.02)*	12.04 (2.95)*
45 mph – 701–750 ft	10.69 (2.13)*	9.28 (2.02)*	10.00 (2.95)*
45 mph – 651–700 ft	10.07 (2.12)*	8.99 (2.02)*	10.28 (2.95)*
45 mph – 601–650 ft	10.10 (2.12)*	9.07 (2.02)*	10.42 (2.95)*
45 mph – 551–600 ft	9.96 (2.12)*	8.81 (2.02)*	10.34 (2.95)*
45 mph – 501–550 ft	9.76 (2.12)*	8.55 (2.02)*	10.06 (2.95)*
45 mph – 451–500 ft	9.29 (2.12)*	8.01 (2.02)*	9.63 (2.95)*
45 mph – 401–450 ft	8.60 (2.12)*	7.42 (2.02)*	8.92 (2.95)*
45 mph – 351–400 ft	7.61 (2.12)*	6.53 (2.02)*	8.01 (2.95)
45 mph – 301–350 ft	6.16 (2.12)*	5.66 (2.02)*	6.90 (2.95)
45 mph – 251–300 ft	4.21 (2.12)	4.23 (2.02)	5.21 (2.95)
45 mph – 201–250 ft	1.54 (2.12)	1.97 (2.02)	2.87 (2.95)
45 mph – 151–200 ft	-2.40 (2.12)	-0.70 (2.02)	-0.22 (2.95)
45 mph – 101–150 ft	-8.21 (2.12)*	-4.19 (2.02)	-4.15 (2.95)
45 mph – 51–100 ft	-15.97 (2.13)*	-9.03 (2.02)*	-8.80 (2.95)*
45 mph – 0–50 ft	-22.17 (2.13)*	-14.55 (2.02)*	-13.47 (2.95)*
50+ mph – 851+ ft	17.20 (2.13)*	13.24 (2.10)*	16.14 (3.45)*
50+ mph – 801–850 ft	17.10 (2.13)*	13.04 (2.10)*	15.90 (3.45)*
50+ mph – 751–800 ft	16.86 (2.13)*	12.77 (2.10)*	15.69 (3.45)*
50+ mph – 701–750 ft	16.43 (2.13)*	12.35 (2.10)*	15.23 (3.45)*
50+ mph – 651–700 ft	14.99 (2.13)*	11.38 (2.10)*	14.38 (3.45)*
50+ mph – 601–650 ft	13.79 (2.13)*	10.10 (2.10)*	13.96 (3.45)*
50+ mph – 551–600 ft	13.12 (2.13)*	9.54 (2.10)*	13.56 (3.45)*
50+ mph – 501–550 ft	12.46 (2.13)*	8.99 (2.10)*	13.11 (3.45)*
50+ mph – 451–500 ft	11.56 (2.13)*	8.20 (2.10)*	12.57 (3.45)*
50+ mph – 401–450 ft	10.49 (2.13)*	7.35 (2.10)*	11.89 (3.45)*
50+ mph – 351–400 ft	9.11 (2.13)*	6.19 (2.10)*	10.90 (3.45)*
50+ mph – 301–350 ft	7.47 (2.13)*	4.96 (2.10)	9.70 (3.45)*
50+ mph – 251–300 ft	5.35 (2.13)	3.61 (2.10)	8.37 (3.45)
50+ mph – 201–250 ft	2.28 (2.13)	1.04 (2.10)	6.57 (3.45)
50+ mph – 151–200 ft	-1.45 (2.13)	-2.36 (2.10)	4.03 (3.45)
50+ mph – 101–150 ft	-6.937 (2.13)*	-6.48 (2.10)*	0.55 (3.45)
50+ mph – 51–100 ft	-15.56 (2.13)*	-12.01 (2.10)*	-4.65 (3.45)

Parameter	Estimate (standard error)		
	Yielded to VRU	Did Not Yield to VRU	VRU Not Present
50+ mph – 0–50 ft	-24.18 (2.13)	-19.37 (2.10)*	-10.47 (3.45)*
Random effects	Standard deviation	Standard deviation	Standard deviation
Site ID	2.40	1.98	3.33
Vehicle ID (nested within site)	3.75	4.08	3.71

Note: * = estimate is statistically significant at 95% confidence interval; na = not applicable

A key observation from the analyses was the relationship between the observed braking distances and the recommended stopping sight distance (SSD) as per design guidelines for each speed limit category (AASHTO, 2018). Figure 5 shows the average speed profiles of yielding drivers at the three speed limit categories. The minimum recommended SSD per the American Association of State Highway and Transportation Officials or AASHTO design guidelines are also indicated for each of the three speed limits. At 30 mph, 45 mph, and 50+ mph sites, the vehicles that yielded to VRUs began braking at approximately 300 ft, 500 ft, and 700 ft upstream of the crosswalk, respectively. These distances align with about 1.4 to 1.5 times the SSD required for each corresponding speed limit, which are 200 ft, 360 ft, and 495 ft at speed limits of 30 mph, 45 mph, and 55 mph, respectively. Figure 5 visually shows the speed selection of drivers in comparison to the SSD for each speed limit, showing consistency in driver behavior relative to safe SSD. This finding shows the importance of providing adequate sight lines on roundabout approaches for drivers to safely yield to pedestrians and bicyclists.

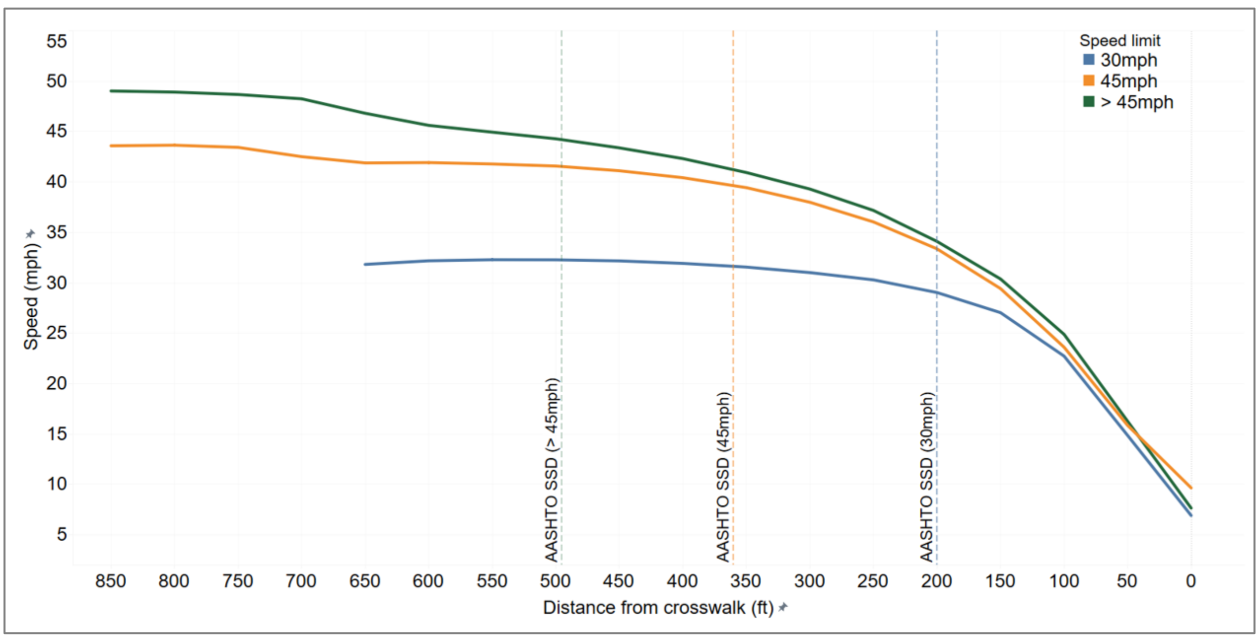

Figure 6 Vehicle Speed Trajectories of Drivers that Yielded to VRU at Crosswalk based on Approach Speed Limits

Chapter 6: Conclusions, Recommendations, and Future Work

This study involved a series of field evaluations at roundabouts to discern how various site-specific features impact drivers' yielding and speed selection behavior toward people walking and biking at roundabouts. Crossing events were staged at 16 roundabout locations in Minnesota to examine yielding response of drivers as they entered and exited a roundabout. Similarly, the speed selection behavior of drivers approaching a roundabout crosswalk was recorded using high-fidelity light detection and ranging (lidar), both in the presence and absence of pedestrians and bicyclists.

These data provided important insights into the interaction between drivers and non-motorized users at roundabouts. The project has resulted in several important findings and subsequent guidelines for MnDOT and other transportation agencies that are aimed at improving the safety of roundabouts, particularly for people walking and biking at these locations. The successful implementation of these findings is anticipated to reduce the crash risk and improve safety of all users at roundabouts. These reductions in crash frequency, particularly the reduction in crashes that involve vulnerable road users (pedestrians and bicyclists) are also expected to reduce the road user costs associated with crashes.

6.1 Conclusions and Recommendations

This study provides important insights into the interaction between drivers and non-motorized users at roundabouts. Compared to other types of intersections, crossing a roundabout on foot or bicycle presents different risks and necessitates that drivers yield to these other road users.

Yield rates toward pedestrians and bicyclists generally exceeded 80% at roundabout entrances. However, the average yield rates at roundabouts exits were less than 40%. Two related reasons can explain this trend. First, drivers tend to accelerate as they exit the roundabout. And second, there is typically little storage available for vehicles queued at the exit crosswalk on a roundabout. This may result in less willingness to stop while exiting to avoid impeding the circulating traffic.

Yield rates were consistently higher when crossing from an island (splitter or bypass) instead of crossing from the curb, possibly because pedestrians at the island may be perceived as already engaged in crossing, prompting drivers to yield due to the legal requirement to yield to pedestrians in the crosswalk. In addition, yield rates on exits were higher among drivers who were turning right (i.e., using the first exit) as opposed to those attempting a left or through movement from their entry approach. This again emphasizes that improving visibility of people walking and biking at roundabouts may help improve overall yield rates. Lastly, the increased complexity of navigation and higher volumes generally associated with multilane roundabouts or roundabouts with multiple travel lanes also reduced yield rates on both entry and exit.

Beyond yielding, the presence of a pedestrian or bicyclist intending to cross the roundabout at entry significantly influenced the speed selection behavior of drivers. Specifically, drivers tended to maintain higher speeds when no road users were present at the crosswalk. In situations when a pedestrian or bicyclist was present, the drivers who yielded typically started braking more rapidly at distances 300-700 ft upstream of the crosswalk. This finding implies that driver awareness and perception of pedestrians and cyclists are crucial factors in ensuring their safety at roundabout entries.

Based on the findings of this study, the following recommendations are made to MnDOT and other transportation agencies in Minnesota, particularly at locations where there are moderate to high volumes of people walking and biking. MnDOT should consider incorporating the recommendations of this study in their ongoing efforts to develop the *Facility Design Guide*, earlier known as the *Road Design Manual* (MnDOT, 2024).

1. Drivers should have a clear line of sight of the crosswalk and the potential crossing locations (curb, splitter island) to increase the visibility of pedestrians and bicyclists. At entry, the line of sight should be based on the stopping sight distance (SSD), which varies by speed. The minimum recommended sight distance at roundabout entries is 1.5 times the SSD. At roundabout exits, sight lines should balance visibility with the need to moderate vehicle speeds and manage driver focus on potential conflicts.
2. Traffic calming measures should be considered at roundabout exits to reduce vehicle speeds. These could potentially include treatments such as raised exit crosswalks or narrower lanes, though additional research is warranted to evaluate their effectiveness.
3. Roundabouts with multiple circulating lanes or multiple approach lanes should be given special consideration, as they present increased challenges for drivers yielding to pedestrians and cyclists. These sites represent promising candidates for enhanced signage and pavement markings to increase drivers' attention to pedestrians and cyclists and associated yielding rates. Where feasible, a highly effective treatment is to re-stripe multi-lane roundabouts to a single circulating lane if traffic volumes permit. Additional measures, such as high visibility crosswalks, can also be considered at such locations.
4. Consider installing rectangular rapid flashing beacons (RRFBs) at sites with lower yield rates or where safe gaps for pedestrians and cyclists are difficult to obtain, particularly at the exits from the roundabout. While sites with RRFBs showed higher yield rates compared to similar sites without these devices, the difference in rates was not particularly large. As such, installation should be considered on a case-by-case basis. RRFBs should not be used in locations where FHWA guidance advises against their application, such as high-speed environments (posted speed limits of 40 mph or higher) (Blackburn et al., 2018).
5. The changes in vehicle speeds when approaching a roundabout were more rapid within a 300-700-ft approach to the crosswalk, depending on the approach speed limit. Thus, it is important to ensure that existing advance warning signage, such as Yield Ahead and Advisory Speed signs, are well-placed and visible to drivers. Additional signage should be considered only if evaluations indicate a need for improved driver awareness at specific locations.

6.2 Limitations and Future Work

The presence of general types of signage (e.g., W11-2, R1-6a) at or in advance of the roundabouts was also evaluated, but did not show any meaningful impacts on yielding behavior. With that said, most of the locations included similar signing plans, making it difficult to assess any sign-related impacts. As such, future evaluations could identify sites with varying static pedestrian signage configurations to better understand their impacts on driver behavior.

This study only examined the speed selection behavior of motorists on the roundabout approach. Future evaluations could also consider investigating speed selection behavior at roundabout exits to better understand the accelerating behavior while exiting, which could in turn provide additional insights as to improving yield rates on exit. Future research can also investigate the effectiveness of speed calming measures such as raised crosswalks, rumble strips, etc., on both roundabout entry and exit.

Another potential limitation of this study is the reliance on staged crossing events. The staged crossings were conducted to ensure a sufficiently large sample and also to provide safety for those engaged in the crossing events. However, while this method is intended to indicate the individual's intention to cross, some drivers may interpret these actions differently. Future research may assess alternate ways to measure driver-pedestrian interactions at crosswalks to better understand the nuances of driver interpretation of pedestrian behavior in diverse contexts.

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Appendix A
Details of Roundabout Sites

This appendix provides location details of each of the 16 roundabout locations, along with an aerial image of the site and the street view of the approach along which the field data were collected.

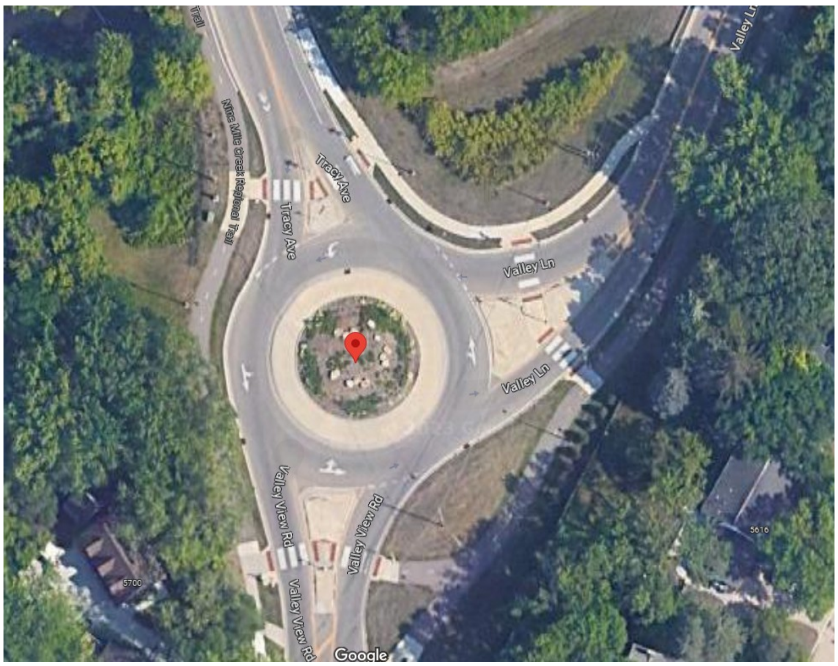
Site 1: 4th St./E College Dr.	
Location	Brainerd (Crow Wing County)
Roundabout configuration	Three-legged double lane
Approach lanes	2 (balanced)
Two-way AADT (veh/day)	6,900 (NB), 6,000 (SB), 12,100 (EB)
Data collection approach	4th St. NB
Posted speed limit	30 mph (EB-WB); not posted in NB
Pedestrian crossing signage	Traditional signage on both entrance and exit
Proposed data collection method	Camera
Roundabout coordinates	[46.34887, -94.20373]
Lidar coordinates	Not applicable

Site 2: 66th St./Nicollet Ave.	
Location	Richfield (Hennepin County)
Roundabout configuration	Four-legged double lane
Approach lanes	2/1 (unbalanced)
Two-way AADT (veh/day)	10,177 (NB), 9,937 (SB), 14,883 (EB), 12,454 (WB)
Data collection approach	EB 66th St.
Posted speed limit	35 mph on all approaches
Pedestrian crossing signage	Traditional signage + in-street signage on both entrance and exit + RRFB on all approaches
Proposed data collection method	Camera
Roundabout coordinates	[44.88344, -93.27819]
Lidar coordinates	Not applicable

Site 3: TH 316 (Red Wing Blvd.)/Tuttle Dr.	
Location	Hastings (Dakota County)
Roundabout configuration	Four-legged single lane
Approach lanes	1 (balanced)
Two-way AADT (veh/day)	7,502 (EB/WB); No data for NB/SB
Data collection approach	NB STH 316
Posted speed limit	45 mph (NB); 35 mph (SB); not posted WB-EB
Pedestrian crossing signage	Traditional signage on exit + in-street signage on both entrance and exit
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	[44.70766, -92.83693]
Lidar coordinates	[44.7054871, -92.8338564]

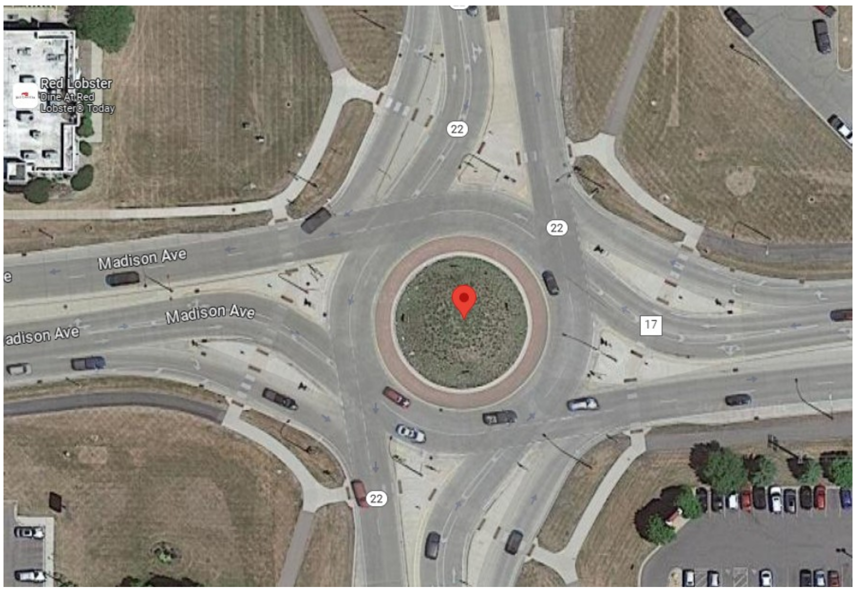
Site 4: US 61-US 10/Jamaica Ave S/W Point Douglas Rd S	
Location	Cottage Grove (Washington County); Located on exit ramp
Roundabout configuration	Five entry approaches; double lane
Approach lanes	2/1 (unbalanced)
Two-way AADT (veh/day)	9,509 (NB/SB); 2,267 (EB/WB); 6,996 (exit ramp)
Data collection approach	EB exit ramp; EB on-ramp
Posted speed limit	45 mph (major); 40 mph (minor); exit ramp serves 65 mph freeway
Pedestrian crossing signage	Traditional signage on exit only
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	[44.81452, -92.93504]
Lidar coordinates	[44.8162439, -92.9369408]

Site 5: Valley View Rd./Tracy Ave./Valley Ln.	
Location	Edina (Hennepin County)
Roundabout configuration	Three-legged single lane
Approach lanes	1 (balanced)
Two-way AADT (veh/day)	15,100 (SB), 9,500 (EB), 3,500 (WB)
Data collection approach	SB Tracy Ave.
Posted speed limit	25 mph on all approaches
Pedestrian crossing signage	Traditional signage on entrance and exit + RRFB
Proposed data collection method	Camera
Roundabout coordinates	44.88459, -93.36872
Lidar coordinates	Not applicable



Site 6: W College Dr/Mississippi Pkwy-SW 4th St	
Location	Brainerd (Crow Wing County)
Roundabout configuration	Four-legged double lane
Approach lanes	2/1 (unbalanced)
Two-way AADT (veh/day)	3,750 (NB/SB), 11,400 (EB), 12,100 (WB)
Data collection approach	SB 4th St.
Posted speed limit	30 mph on all approaches
Pedestrian crossing signage	Traditional signage on entrance and exit
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	46.34734, -94.21218
Lidar coordinates	46.349650, -94.212198

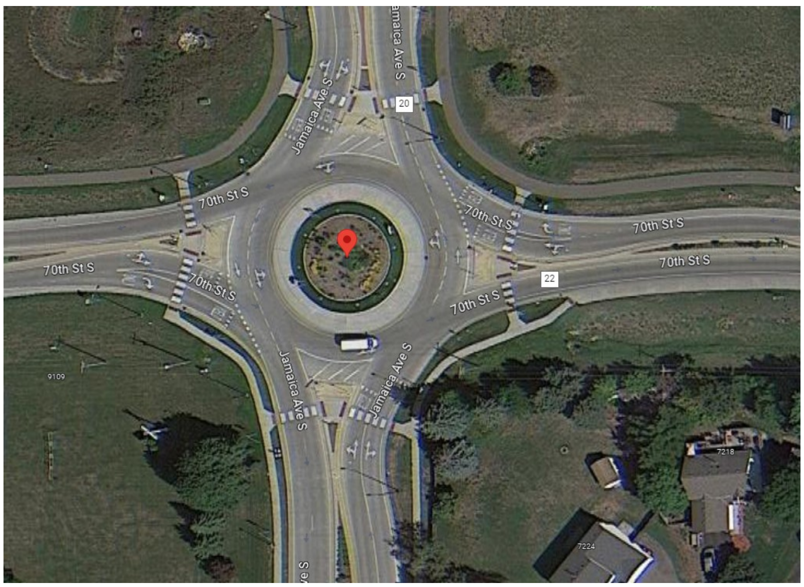
Site 7: Madison Ave/TH 22	
Location	Mankato (Blue Earth County)
Roundabout configuration	Four-legged double lane
Approach lanes	2 thru and 1 exclusive right (balanced)
Two-way AADT (veh/day)	18,226 (NB), 21,431 (SB), 16,944 (EB), 4,126 (WB)
Data collection approach	WB Madison Ave.
Posted speed limit	45 mph on all approaches
Pedestrian crossing signage	Traditional signage on exit only + In-street signs on entrance and exit
Proposed data collection method	Camera
Roundabout coordinates	44.16688, -93.94904
Lidar coordinates	Not applicable



Site 8: TH 95/N Rum River Dr	
Location	Princeton (Mile Lacs County)
Roundabout configuration	Four-legged single lane
Approach lanes	2 (balanced)
Two-way AADT (veh/day)	10,400 (NB), 7,400 (SB), 6,833 (EB), 9,012 (WB)
Data collection approach	WB TH95
Posted speed limit	45 mph (WB-EB); 30 mph (NB-SB)
Pedestrian crossing signage	Traditional signage on entrance and exit
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	[45.57405, -93.58005]
Lidar coordinates	[45.574119, -93.576383]

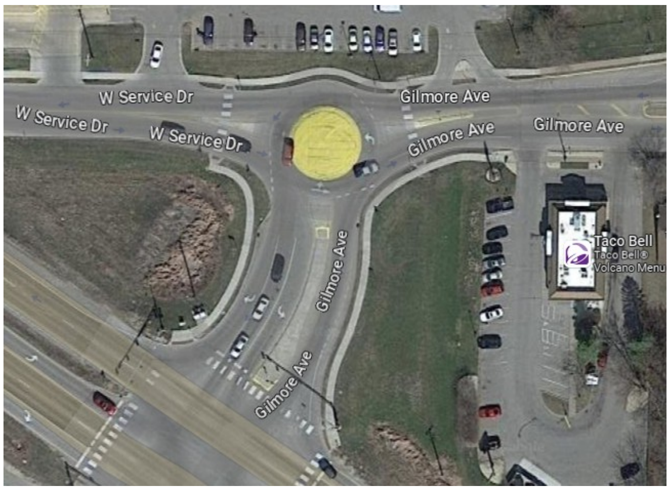
Site 9: Territorial St E/Lewis Ave N	
Location	Watertown (Carver County)
Roundabout configuration	Four-legged single lane
Approach lanes	1 (balanced)
Two-way AADT (veh/day)	2,950 (NB/SB), 6,000 (EB), 9,300 (WB)
Data collection approach	EB Territorial St.
Posted speed limit	30 mph on all approaches
Pedestrian crossing signage	None
Proposed data collection method	Camera
Roundabout coordinates	44.96369, -93.847
Lidar coordinates	Not applicable

Site 10: 70th St S/Jamaica Ave S	
Location	Cottage Grove (Washington County)
Roundabout configuration	Four-legged double lane
Approach lanes	2 on NB-SB, 1 thru + exclusive right on EB/WB (unbalanced)
Two-way AADT (veh/day)	6,802 (NB), 4,350 (SB), 6,600 (EB), 4,704 (WB)
Data collection approach	WB 70th St.
Posted speed limit	50 mph (WB-EB); 45 mph (NB-SB)
Pedestrian crossing signage	Traditional signage on exit only + In-street signs on entrance and exit
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	44.84808, -92.92185
Lidar coordinates	44.84812, -92.9173791

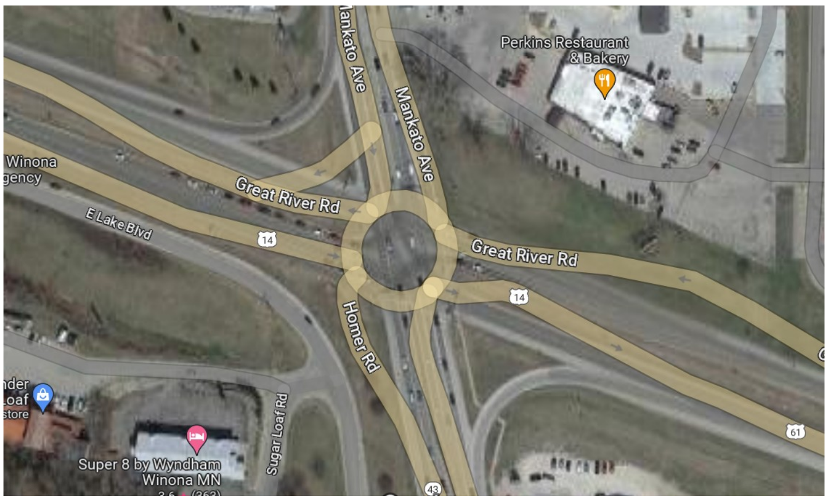


Site 11: I 35/Rice Creek Pkwy-Thumb Rd / CR1	
Location	Arden Hills (Ramsey County)
Roundabout configuration	Five approach legs; single lane
Approach lanes	1 (balanced)
Two-way AADT (veh/day)	4,429 (NB/SB), 6,521 (EB), 3,883 (WB), 2,950 (one-way ramp)
Data collection approach	WB CR1
Posted speed limit	40 mph (WB-EB); 35 mph (SB); 30 mph (NB); exit ramp serves freeway posted at 65 mph
Pedestrian crossing signage	Traditional signage on exits only
Proposed data collection method	Camera
Roundabout coordinates	45.10787, -93.18665
Lidar coordinates	Not applicable

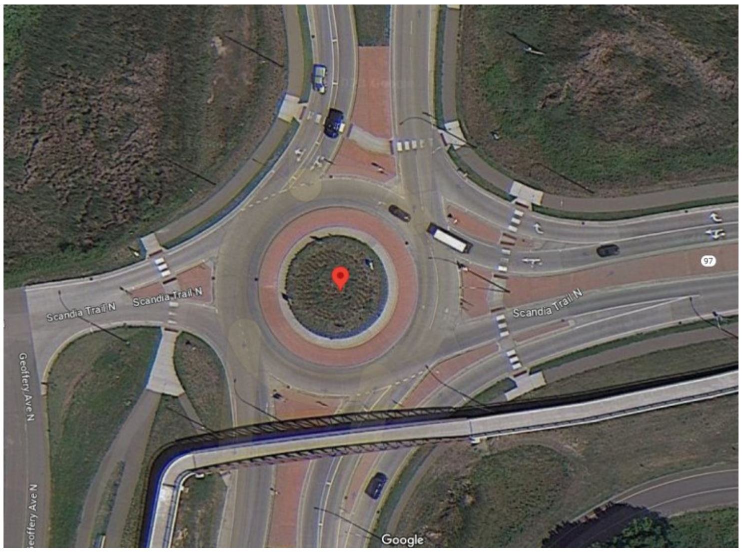
Site 12: Gilmore Ave./W Service Dr./US 14 Connector	
Location	Winona (Winona County)
Roundabout configuration	Three-legged single lane
Approach lanes	1 (balanced)
Two-way AADT (veh/day)	6,200 (major); no data (minor)
Data collection approach	EB Service Dr.
Posted speed limit	30 mph (WB-EB); NB is connector to US 14
Pedestrian crossing signage	Traditional signage on entrance and exit + RRFB (confirm with MnDOT; Google view does not show RRFB)
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	[44.04861, -91.67638]
Lidar coordinates	[44.0496151, -91.6792529]



Site 13: US 14/TH 43	
Location	Winona (Winona County)
Roundabout configuration	Four-legged double lane
Approach lanes	2/1 (unbalanced)
Two-way AADT (veh/day)	19,900 (EB), 12,400 (WB), 22,400 (SB), 17,700 (NB)
Data collection approach	EB US 14
Posted speed limit	55 mph (EB/WB), 45 mph (NB/SB)
Pedestrian crossing signage	Traditional signage on entrance and exit + RRFB
Proposed data collection method	14
Roundabout coordinates	Camera + LIDAR
Lidar coordinates	[44.029573, -91.62218]

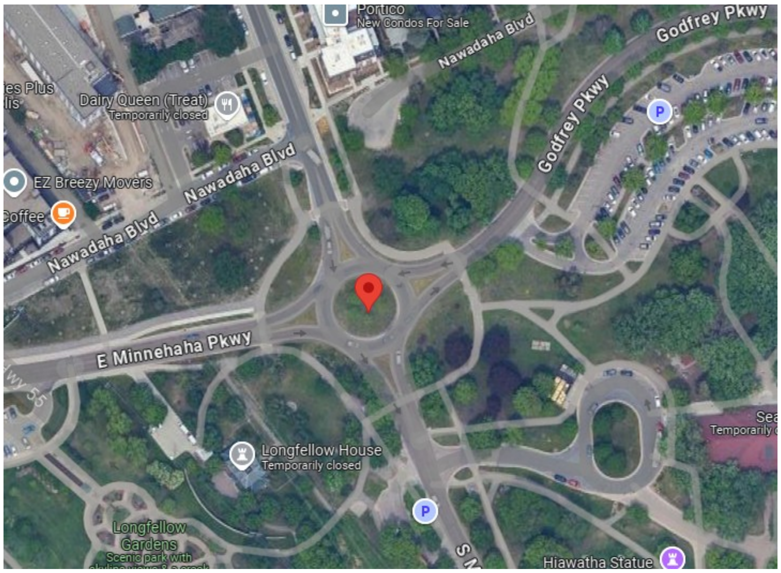


Site 14: US 61/TH 97 (North Junction)	
Location	Forest Lake (Washington County)
Roundabout configuration	Four-legged double lane
Approach lanes	2/1 (unbalanced)
Two-way AADT (veh/day)	22,000 (NB), 19,700 (SB), 15,300 (WB)
Data collection approach	WB STH97
Posted speed limit	50 mph (NB-SB); 55 mph (WB)
Pedestrian crossing signage	Traditional signage on exit only
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	[45.2599, -92.98339]
Lidar coordinates	[45.2603254, -92.9798517]



Site 15: TH 22/Adams St.	
Location	Mankato (Blue Earth County)
Roundabout configuration	Four-legged double lane
Approach lanes	2/3 (unbalanced) exclusive right on NB/SB, and WB
Two-way AADT (veh/day)	21,431 (NB), 30,254 (SB), 9,500 (EB), 11,782 (WB)
Data collection approach	NB TH22
Posted speed limit	45 mph (NB-SB); 30 mph (EB-WB)
Pedestrian crossing signage	Traditional signage on exit only + In-street signs on entrance and exit
Proposed data collection method	Camera + LIDAR
Roundabout coordinates	[44.17045, -93.94901]
Lidar coordinates	[44.1677595, -93.9489188]

Site 16: Minnehaha Ave./Godfrey Pkwy.	
Location	Minneapolis (Hennepin)
Roundabout configuration	Four-legged single lane
Approach lanes	1 (balanced)
Two-way AADT (veh/day)	5,500 (EB-WB); 7,510 (NB-SB)
Data collection approach	EB Minnehaha Pkwy
Posted speed limit	20 mph (all directions)
Pedestrian crossing signage	Traditional signage + In-street signs
Proposed data collection method	Camera
Roundabout coordinates	44.91655, -93.21317
Lidar coordinates	Not applicable



Appendix B

Speed Selection Profile by Site

This appendix provides average speed selection profiles for each of the 9 roundabout sites where lidar speed data were collected during field evaluations at roundabout entry. The profiles are shown based on speeds interpolated at every 50-foot interval, which are averaged across all drivers. The speed profiles are presented for three scenarios- 1) when no VRU is present at the roundabout crosswalk, 2) when a pedestrian is waiting to cross the roundabout, and 3) when a bicyclist is waiting to cross the roundabout. Speed profiles for the second and third scenarios are further distinguished based on whether the driver yielded to the VRU or not.

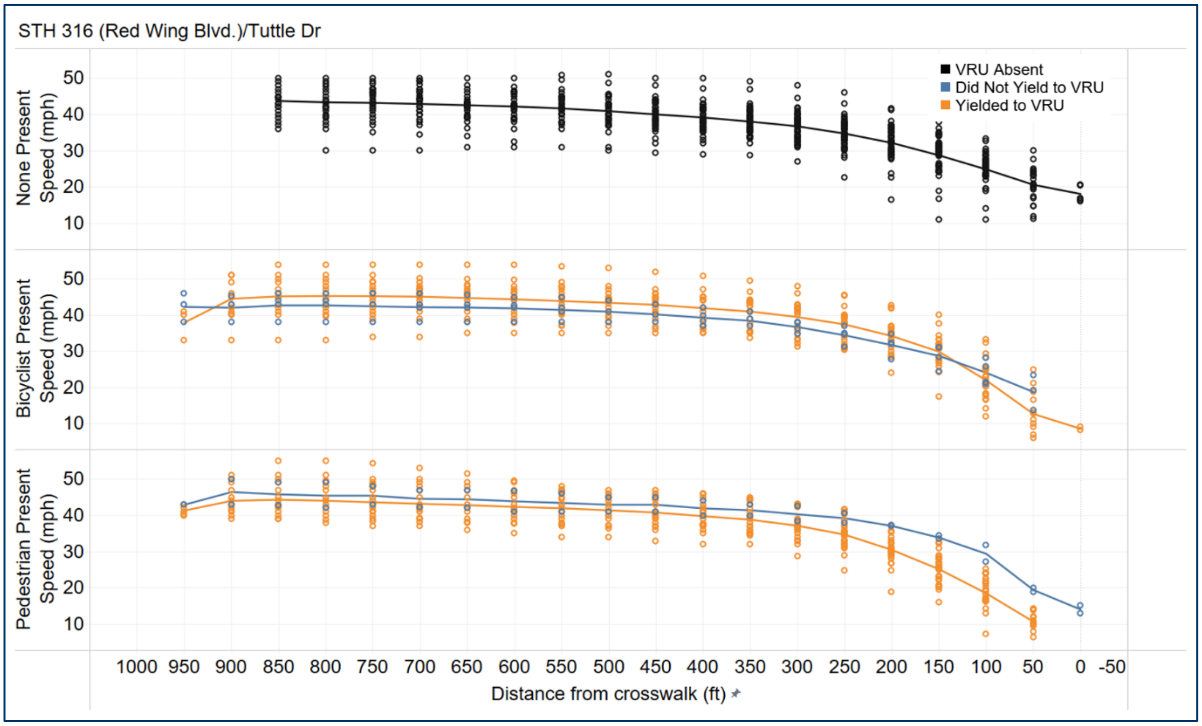


Figure 7 Average Speed Profiles as Vehicles Approach Roundabout at STH316/Tuttle Dr.

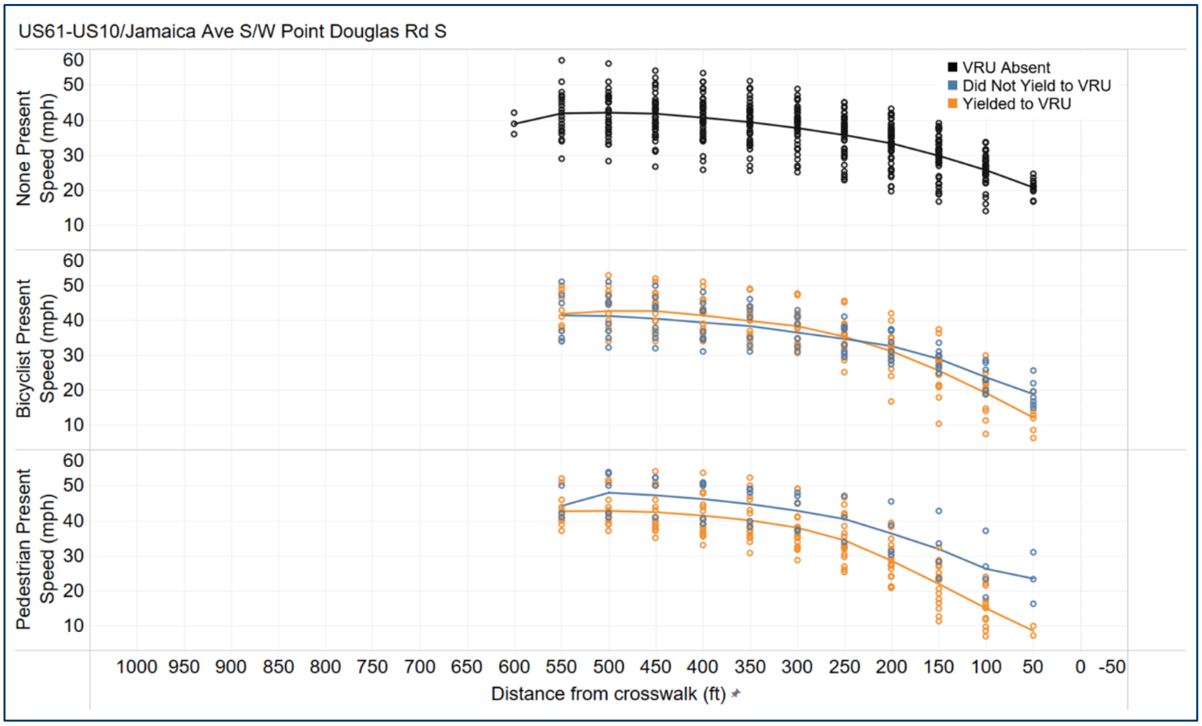


Figure 8 Average Speed Profiles as Vehicles Approach Roundabout at US61-US10/Jamaica Ave S/W Point Douglas Rd S

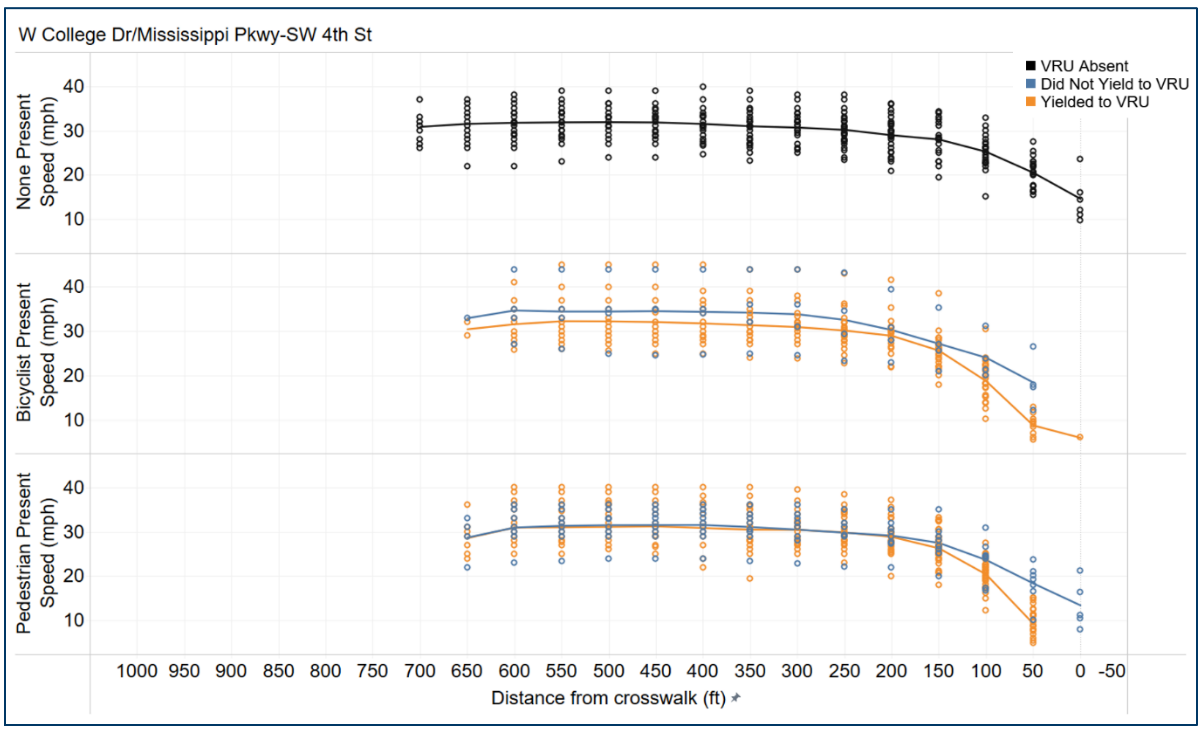


Figure 9 Average Speed Profiles as Vehicles Approach Roundabout at W College Dr/Mississippi Pkwy-SW 4th St

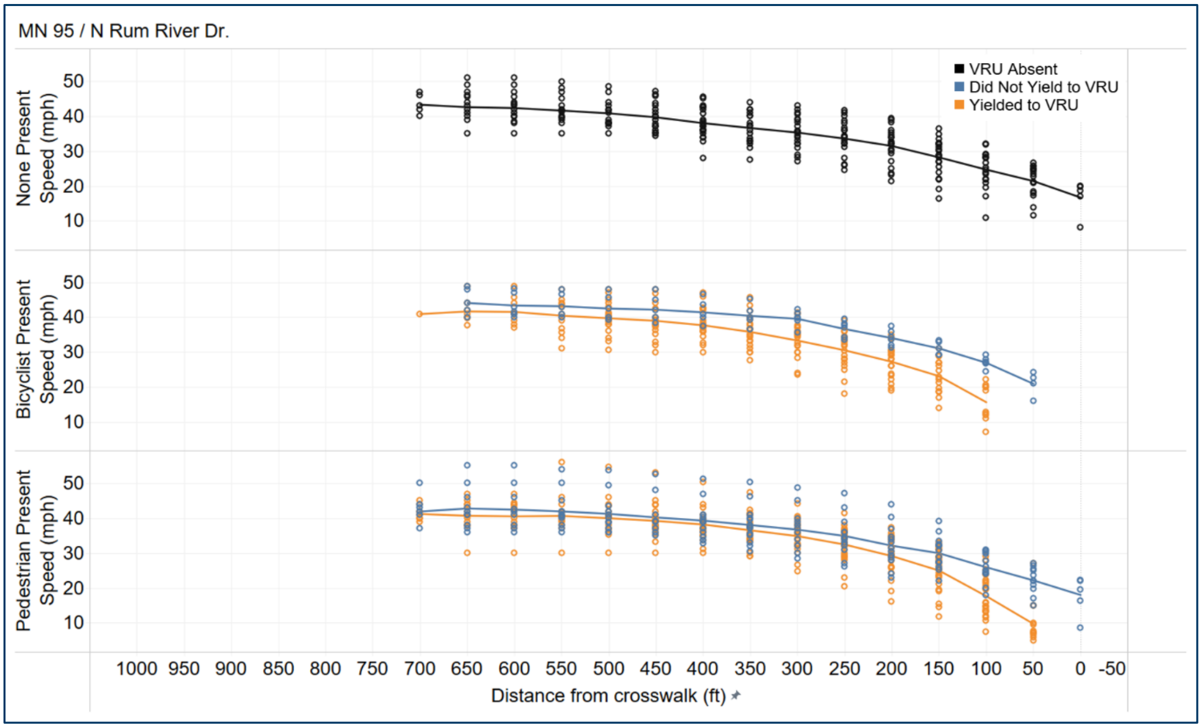


Figure 10 Average Speed Profiles as Vehicles Approach Roundabout at TH95 / N Rum River Dr

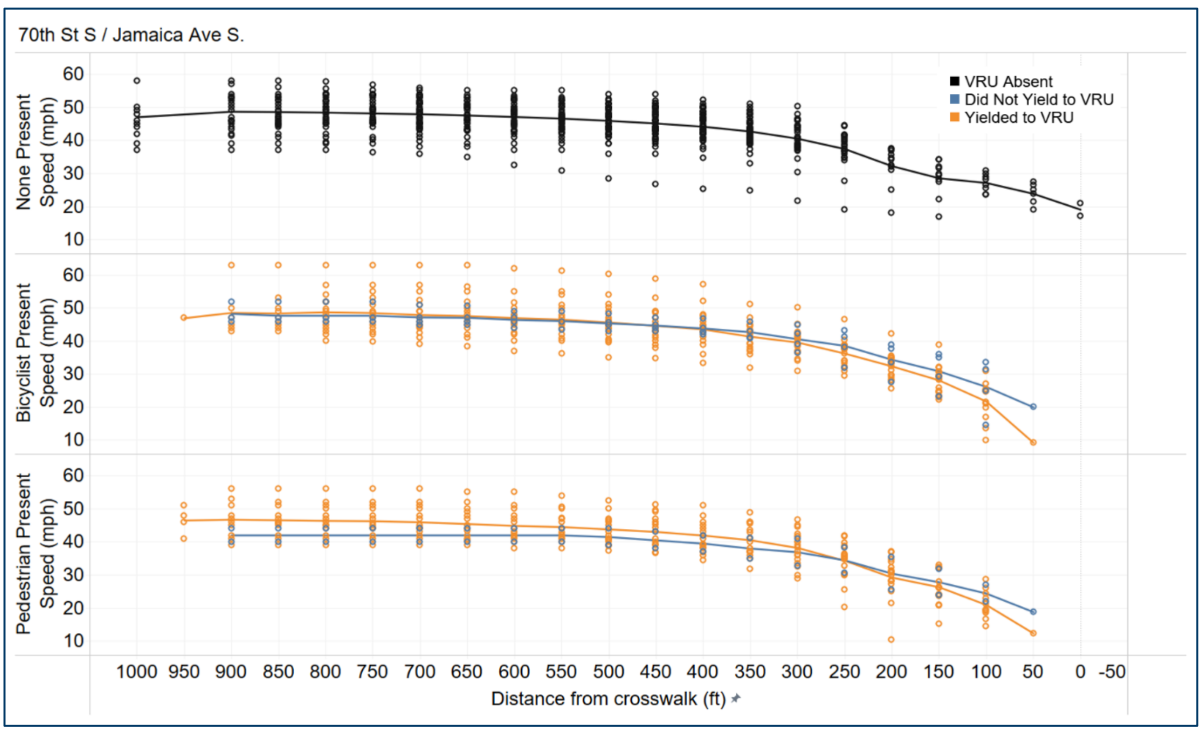


Figure 11 Average Speed Profiles as Vehicles Approach Roundabout at 70th St S / Jamaica Ave S

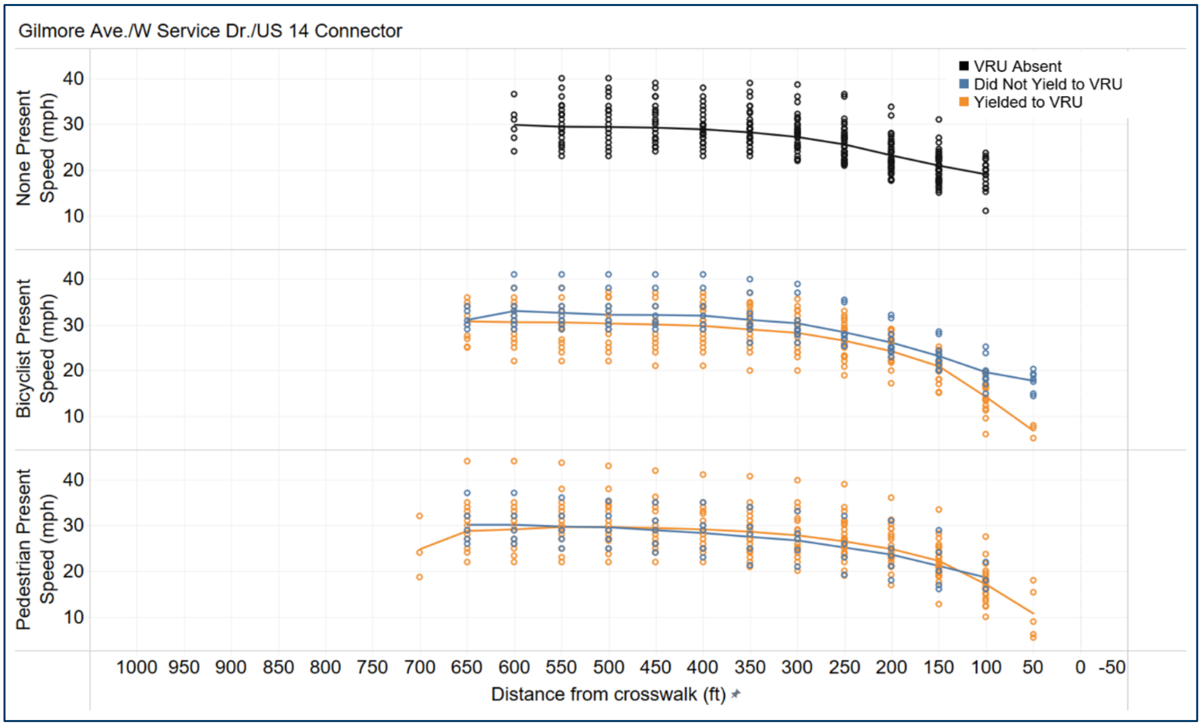


Figure 12 Average Speed Profiles as Vehicles Approach Roundabout at Gilmore Ave. / W Service Dr. / US 14 Connector

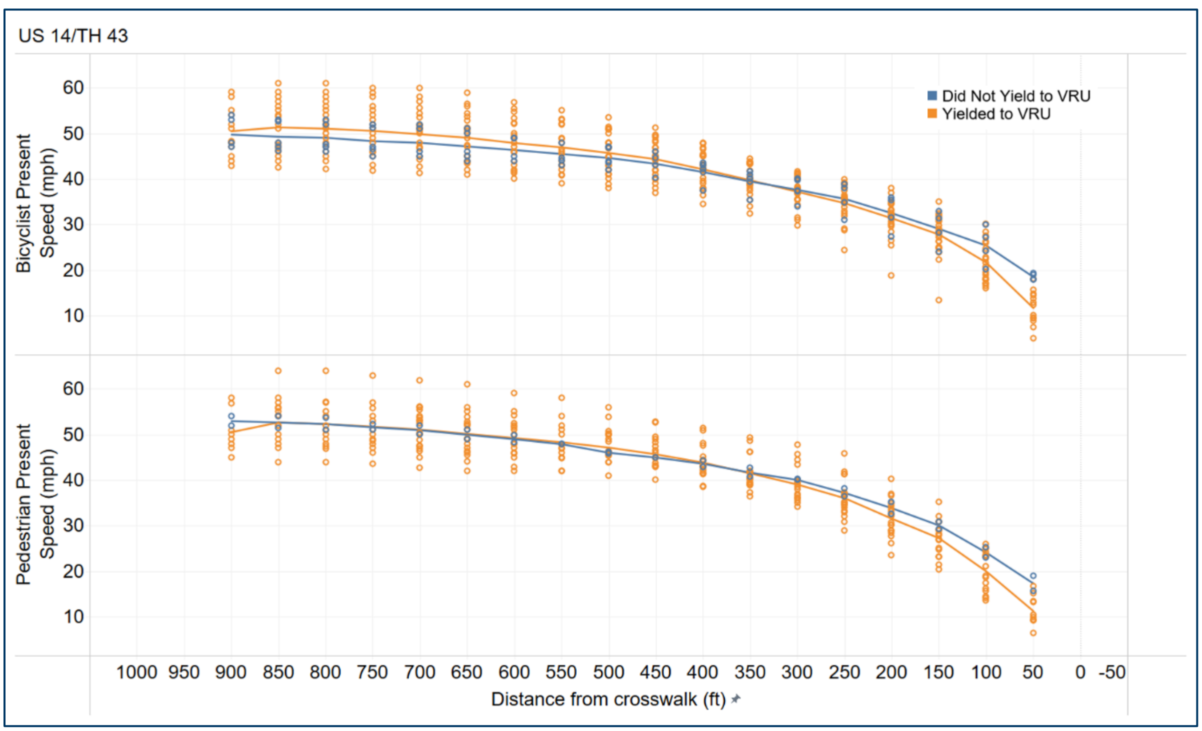


Figure 13 Average Speed Profiles as Vehicles Approach Roundabout at US 14/TH43

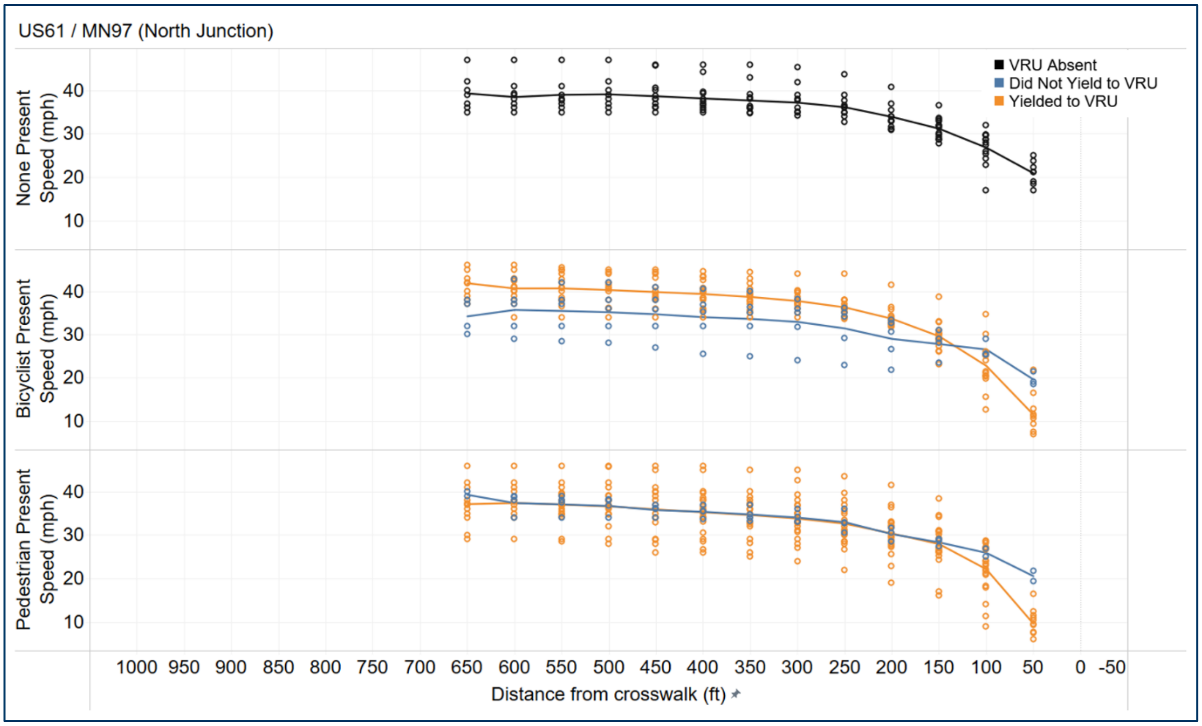


Figure 14 Average Speed Profiles as Vehicles Approach Roundabout at US61 / TH97 (North Junction)

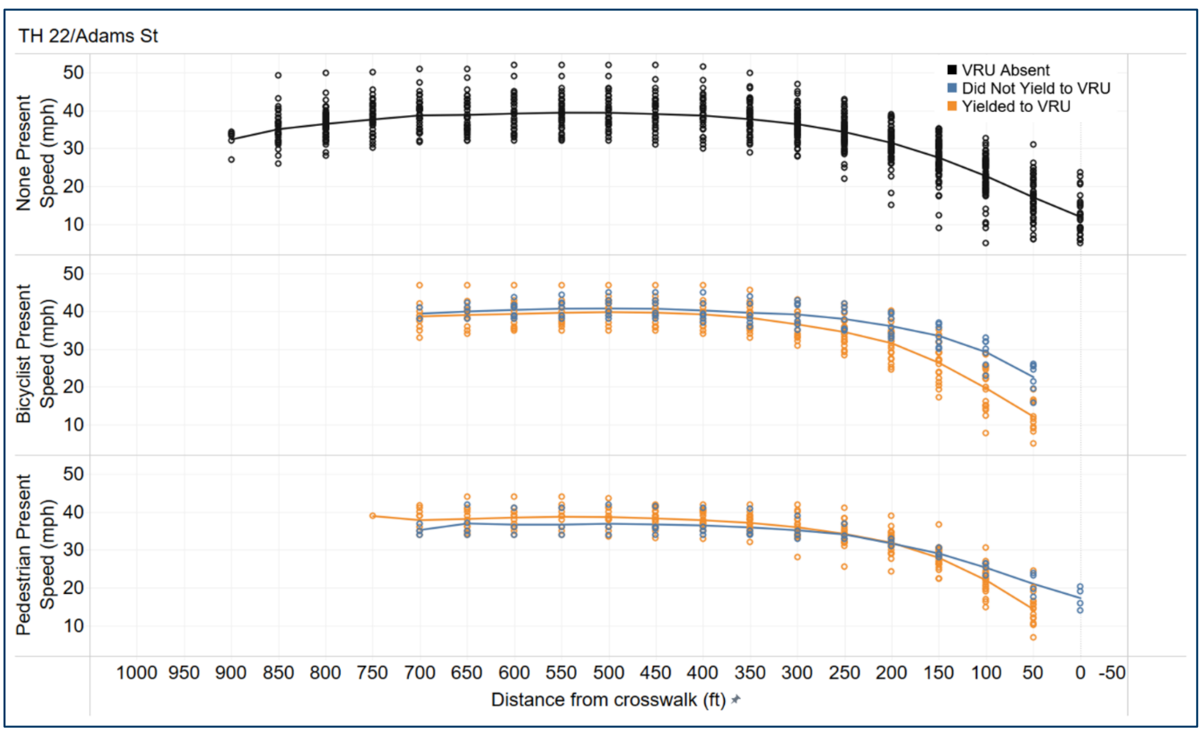


Figure 15 Average Speed Profiles as Vehicles Approach Roundabout at TH22/Adams St.