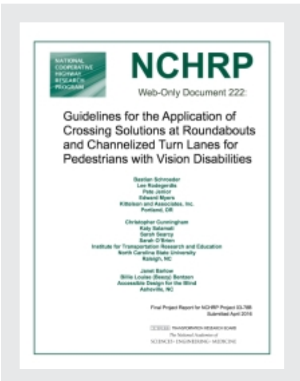
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Guidelines for the Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities

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1 INTRODUCTION

This document is the draft final report of NCHRP Project 03-78B*: Guidelines for the Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*. The primary deliverable of the project is a guidebook to provide guidance to engineers and planners on the design of roundabouts and channelized turn lanes (CTLs) for accessibility. The guidebook is available as a standalone publication.

The accessibility of modern roundabouts and intersections with channelized (right) turn lanes is an important civil rights challenge in the United States that has broad potential implications for engineering practice in this country. The recently completed NCHRP Project 3-78A contributed significant conceptual, empirical, and analytical content to this accessibility discussion and resulted in published *NCHRP Report 674: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities* (Schroeder et al., 2011a). This project builds on the results and lessons learned in NCHRP 03-78A, and is tasked with developing a guidebook to serve as a hands-on resource for practitioners.

NCHRP Project 03-78A was tasked with identifying and testing crossing solutions to assist pedestrians with vision impairments in crossing at modern roundabouts and at intersections with channelized turn lanes. The key products of that project included: (I) a framework for empirical study and analysis of accessibility performance, (II) identification and field testing of several treatments, and (III) research extension through modeling and simulation to expand the results beyond the field-tested sites.

This research has the unique opportunity to advance the knowledge developed through NCHRP 3-78A by delivering (a) additional and streamlined field work targeting key knowledge gaps, (b) new prediction models tailored to crossing performance by pedestrians who are blind, (c) validation of previously-developed models with independent data, and (d) the development of engineering guidelines for the application of accessibility treatments. Since the publication of NCHRP Report 674, a significant amount of additional accessibility research has been conducted nationally. New research results available to support the guidelines development of this project include:

- Before-and-after evaluation of two multi-lane roundabouts in Oakland County, Michigan equipped with Pedestrian Hybrid and Rectangular Rapid-Flashing Beacons (RCOC, 2011);
- A Federal Highway Administration Project evaluating the accessibility performance of Rectangular Rapid-Flashing Beacons at multi-lane roundabouts in the US (FHWA, 2011);
- Research on driver yielding behavior at eight US and four international two-lane roundabouts, predicting yielding based on geometric and operational factors (NIH, 2010, NSF 2012;)
- Research on pedestrian crossing behavior and its effect on yielding of right-turning vehicles at signalized intersections (NIH, 2010);
- Research on the effect of crosswalk location and traffic volumes at single-lane roundabouts (Guth et al., 2012) and channelized right turn lanes (Schroeder et al., 2006);
- Research on wayfinding challenges at roundabouts and midblock crossings with a focus on treatments to assist blind pedestrians to locate crosswalks (NIH, 2010);
- Research on nonvisual cues for promoting initial alignment at crosswalks and for staying within the crosswalk while crossing (Scott et. al., 2011a; 2011b); and
- Publication and adoption of the second edition of Roundabouts: An Informational Guide (Rodegerdts, 2010).

This final report documents and summarizes the project activities during the research. The report presents a summary of critical project tasks.

1.1 Research Objectives

There were three major research objectives to NCHRP Project 3-78b:

1. The development of guidelines for the application of crossing solutions and treatment installations that will establish accessibility for pedestrians who are blind and who have low vision at modern roundabouts and channelized turn lanes,
2. The conduct of field-based research to gather accessibility data and test treatments at a broad sample of sites across the country, and
3. The extension of empirical field results through modeling to extrapolate crossing performance and impacts of vehicular traffic beyond the observed range of data.

Guideline development is the first and foremost objective, with the second and third objectives being prerequisites and conduits for achieving the primary objective. The focus of the guidelines is on solutions that can be incorporated in the design phase and that can be installed and fully activated when the site opens to traffic. While engineers are faced with retrofit applications of these treatments, guidance is needed in the design stage to ensure accessibility of a new site in compliance with ADA from opening day. The guidelines consider the trade-offs between the needs of various users of a facility: pedestrians, including pedestrians with vision impairments or other disabilities, bicyclists, and vehicular traffic, including heavy vehicles such as trucks and buses. The developed guidance is intended to be directly usable as a decision-support tool by practicing engineers, while being a useful resource for other stakeholders in accessibility questions.

In order to develop the guidelines for applications of treatments, the second objective is a well-targeted field research plan covering a breadth of sites and targeted to fill critical knowledge gaps in guideline development with empirical data. The research applied a newly developed *Accessibility Audit* study protocol, which streamlines collection of the key accessibility data from, and is applicable to a broad range of sites. The field data collection covered channelized turn lanes, single-lane, and two-lane roundabouts with various existing treatment combinations, including geometric configurations that may reduce speeds, encourage yielding, and thereby support the likelihood of an accessible crossing environment.

The third objective is the enhancement of predictive models that supplement the empirical data collected, and extrapolate field results beyond the observed ranges. In NCHRP Report 674, the research team developed models to predict the delay experienced by a blind pedestrian at the three subject facility types as a function of driver yielding, pedestrian gap acceptance, and the utilization of these crossing opportunities. In parallel research, the team developed models to predict driver yielding and gap acceptance. This research proposed to mirror the delay modeling effort into safety prediction equations, as well as validate other models with new data.

1.2 Target Audience

The guidebook and final report are targeted to an audience of practicing professional engineers, who in some cases may have little to no background in design for accessibility. The guidelines are therefore written in a way that is consistent with other engineering guidebooks (e.g. Roundabouts: An Informational Guide, ITE Traffic Engineering Manual, ITE Manual for Transportation Studies) to ensure its usability. At the same time, the guidelines are written to comply with American with Disabilities Act requirements for accessibility of written or electronic documents (Section 508 compliance), and are consistent with existing guidance on accessible design of pedestrian facilities and public rights of way.

Given the sensitive political nature of this research, it is expected that the audience for these products extends well beyond the engineer tasked with designing a particular site. The group of stakeholders and those interested in this research most certainly includes planners and decision-makers at the municipal and state government levels, as well as FHWA, which is highly interested in establishing accessibility at all sites. The proposed team has a strong record of working collaboratively and effectively with these stakeholders by relying on data-driven and non-confrontational working relationships.

The audience further includes the US Access Board, which is tasked with writing technical specifications for implementing the American with Disabilities Act, and which has published proposed guidelines in the form of the Notice of Proposed Rulemaking for Accessible Pedestrian Facilities in the Public Right-of-Way. The team hopes that the results of this research will be useful to the Access Board by providing additional empirical evidence for or against the accessibility of a particular treatment. While the results of this research may not be available in time for the Final Rule, the team hopes that the results from this project will be instrumental in the discussion of *equivalent facilitation* requirements.

Finally, this project has a broad public interest component, including professionals and researchers in the field of orientation and mobility, as well as private citizens with and without vision impairments. As such, the team is tasked with completing a product that is clear, concise, and technically sound to be useful as engineering guidelines, while also providing the broader context of this research to a much broader audience (presumably in the final project report).

1.3 Organization of Final Report

This chapter provided a general introduction and background for the research. Chapter 2 presents a literature review, including specific discussion on research on crossing, wayfinding, and crossing treatments. Chapter 3 summarizes the study methodology, including field study protocols, site selection, and an overview of modeling efforts. Chapter 4 presents the field study results, including a summary of collected data, and a narrative of observations at the various sites visited. Chapter 5 summarizes the predictive models developed in this research, and Chapter 6 offers conclusions and recommendations.

The main chapters are supported by five appendices. Appendix A presents details on the development of models to predict driver yielding, while Appendix B presents details on the risk model development. Appendix C discusses the approach for crossing sight distance evaluation. Appendix D presents details of the field study results and collected data. Finally, Appendix E presents photo logs of all sites studied as part of this research.

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2 LITERATURE REVIEW

It has been well documented in past research that pedestrians who are blind can face significant accessibility challenges when crossing at modern roundabouts or intersections with channelized right turn lanes. As a result of a systematic and iterative research program, researchers (many of whom are on this team) have documented that significant access challenges exist for individuals with blindness when crossing at roundabouts (e.g. Guth et al., 2005) and channelized turn lanes (e.g. Schroeder et al., 2006). Roundabouts with multiple lanes have been shown to be particularly problematic. For example, Ashmead et al. found that blind pedestrians had greater difficulty than sighted pedestrians when tasked with distinguishing gaps in approaching traffic at a two-lane roundabout that were long enough to cross from those that were not (Ashmead et al., 2005).

2.1 *NCHRP Report 674* Framework for Accessible Crossings

In *NCHRP Report 674: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities* (Schroder et al., 2011a), the research team conceptually divided the crossing task for a blind pedestrian into four distinct components:

1. Finding the crosswalk,
2. Aligning to cross,
3. Deciding when it is safe to cross, and
4. Maintaining alignment during crossing.

The third task is the one that is likely to be most critical to safety. Therefore the focus of the human factors research presented in *NCHRP Report 674* was on the third task. In this project, the team supplemented the primary focus on the third component from earlier work, with field studies on tasks 1, 2 and 4. The motivation for this was to obtain a more complete picture of the wayfinding challenges that roundabouts and CTLs may pose to persons who are blind.

Crosswalks at roundabouts and CTLs are not where pedestrians who are visually impaired are accustomed to finding crosswalks at “conventional” signal or stop-controlled intersections, and, as a result, pedestrians with blindness or low vision may cross well outside the crosswalk, or may cross to the central island if they are unable to locate a crosswalk. Because there is no vehicular traffic parallel to crosswalks at roundabouts, and because this cue normally provides the most reliable information about the direction of the crosswalk, pedestrians who are visually impaired may not establish a heading to cross that is in line with the crosswalk. If they initiate a crossing without aligning accurately, or if they fail to maintain a correct alignment while crossing, they may be outside the crosswalk as they complete their crossing. If there is landscaping that impedes their ability to step out of the street when they arrive at the end of the crossing (e.g., the splitter island if crossing from curb to island, or the curb if crossing from splitter island to curb), they may find it necessary to remain in the vehicular way for some time while they search for an opening that permits them to step out of the street.

The framework to evaluate and quantify crossing performance used a four-criterion assessment that conceptually separates the various components of the crossing task.

1. *Crossing Opportunity Criterion*: Are there sufficient crossing opportunities in the form of yields or crossable gaps?
2. *Crossing Opportunity Utilization Criterion*: Are the crossing opportunities detected and/or utilized by the pedestrian?
3. *Delay Criterion*: Is a crossing opportunity taken within a reasonable time?
4. *Safety Criterion*: Does the crossing interaction occur without a significant degree of risk with an acceptable level of risk?

Arguably, the fourth component, the safety criterion, is the most important aspect to ensure a safe and accessible crossing environment, while the delay criterion is a term typically used in traffic engineering assessments of (sighted) pedestrian Levels of Service. However, all four measures are important in evaluating the accessibility of a crossing and understanding the contributing factors to a decision that may have resulted in high risk or delay. The research protocol in the present research collected data on all four components, and further divided the first and second criteria into sub-components related to crossing opportunities when vehicles yielded upstream of the crosswalk, and crossing opportunities created by gaps when no *vehicles* were approaching from upstream.

From this framework emerge key accessibility performance measures, which include the frequency of orientation and mobility (O&M) interventions (our key measure of risk), and the average and 85th percentile pedestrian delay. Prior research developed predictive models for pedestrian delay as a function of driver yielding, gap availability, and the utilization rates for gaps and yields (Schroder et al., 2011a; Schroeder and Rouphail, 2010). In follow-up work, team members further developed models that predicted driver yielding behavior and pedestrian gap acceptance at midblock crossings using logistic regression models (Schroeder 2008; Schroeder and Rouphail, 2011b; Schroeder and Rouphail, 2011c), and worked on expanding the yielding prediction models so that they could be applied to multi-lane roundabouts (Salamati et al., 2013). A major focus of this research was the calibration and validation of these models with data collected at new sites, the customization of models specific to access for

The key underlying premise of this framework is that the effectiveness of treatments can be represented as a change to one or more of the explanatory variables in these predictive models. For example, a Rectangular Rapid-Flashing Beacon (RRFB) is expected to increase the rate of driver yielding, while a raised pedestrian crosswalk (RPC) is expected to primarily reduce vehicular speed, which has been linked in research to an increased propensity of drivers to yield (Geruschat and Hassan, 2005; Schroeder and Rouphail, 2011b) and reductions in frequency of interventions. Using the logic of the framework, the effectiveness of any given treatment can be evaluated relative to other factors (geometry, speed, volumes, etc.), while being calibrated using data from the research of this project.

In the following sections, previous research on accessibility of roundabouts and CTLs will be summarized in more detail, including research on crossings by pedestrians who are blind, research on wayfinding, and research on crossing treatments intended to enhance accessibility.

2.2 Overview of Previous Research with Blind Participants Regarding Actual Street Crossings and Judgments About When to Cross

Research conducted during the last 15 years has documented the challenges experienced by pedestrians who are blind when crossing at roundabouts and CTLs. Comparisons of totally blind and sighted pedestrians crossing at roundabouts and CTLs show that blind pedestrians miss more crossing opportunities, wait longer to cross, and are more likely to make risky crossings. For example, Guth et al. (2005) investigated blind and sighted participants' road-crossing judgments at three roundabouts in Maryland. Blind participants' judgments were more risky than sighted participants at two higher-volume multi-lane roundabouts, but not at the low-volume single-lane roundabout. At a single-lane roundabout in Tampa (Guth et al, 2013), blind participants' judgments about when to cross were more risky when traffic volume was high compared to judgments made during lower volume times of day. Blind participants also were slower than sighted participants in making crossing judgments, and they accepted fewer crossing opportunities. Both groups made somewhat safer and more efficient judgments at locations farther from the roundabout than at the "typical" crosswalk location one vehicle length back from the circle (Guth et al 2013). Similar comparisons of blind and sighted pedestrians at channelized turn lanes demonstrated similar difference in performance by blind and sighted pedestrians and documented difficulties by blind travelers identifying crossing opportunities and in making safe crossing decisions (Schroeder et al, 2006).

Figure 2-1: Blind pedestrian crossing at multi-lane roundabout

> *This figure shows two pedestrians crossing at a multilane roundabout, one with a white cane extended. Vehicles are yielding in each lane.*

Ashmead et al. (2005) reported the result of a study of six blind and six sighted pedestrians who crossed the street at a double-lane urban roundabout in Nashville under high and low traffic volumes. As in the earlier study in Maryland, blind participants waited longer to begin crossing than sighted participants. About 6% of the blind participants' crossing attempts were judged dangerous enough to require intervention, compared to none for sighted pedestrians. Drivers yielded frequently to pedestrians waiting to cross the entry lanes, but significantly less so on exit lanes. The study showed that sighted participants generally accepted driver yields, whereas blind participants rarely did so, presumably in part because they could not hear the yielding vehicles, or because they weren't comfortable crossing in front of a stopped vehicle.

In recent years, accessibility research involving multi-lane roundabouts has largely moved from descriptive work that documents crossing behavior at various conditions and at various locations to a focus on treatment studies. For example, there have been several evaluations of pavement treatments such as sound strips and raised crosswalks (Hughes et al., 2011; Inman et al., 2005, 2006; Schroeder, 2011) and signalization treatments such as pedestrian hybrid beacons and rectangular rapid-flash beacons (Final Report: Oakland County, 2011; Schroeder et al, 2015).

2.2.1 Crossing in Gaps in Traffic

Crossing in gaps requires relatively large gaps in traffic and a location with minimal ambient noise, neither of which is commonly available at a roundabout or CTL. The fact that long gaps often are infrequent contributes to the relatively long pedestrian delay times that have been reported in several studies (Guth et al., 2013; Schroeder, 2011).

Wall et al. (2008) investigated the auditory detection of approaching vehicles by pedestrians who are blind or who have low vision. The study considered the level of ambient sound; the sound level and speed of approaching vehicles; and physical features of the environment, such as hills, bends in the road, trees, and obstacles. One of their findings is as follows:

"In trials on the straight roadway, as the ambient sound level increased, the detection times decreased. Once the ambient sound level is above approximately 50 dBA, it becomes virtually impossible to hear vehicles far enough away to know whether it is clear enough to be able to complete a crossing before the vehicles arrive."

At CTLs and roundabouts, the ambient sound levels will often be above 50dBA so the safety of crossing in detected gaps in traffic at most roundabouts and CTLs is questionable. In addition, the increase in quieter vehicles has resulted in the need for blind pedestrians to modify the gap detection crossing strategy and to be more conservative in auditory-based gap crossing decisions at uncontrolled crosswalks.

While driver stopping sight distance is often used as a safety measure, its use includes an assumption that drivers can see the pedestrian, are paying attention, and will be able to stop in time for pedestrians in their paths. Pedestrians who are blind cannot easily monitor driver actions and vehicle speed changes (or lack thereof) and revise their speed or position to avoid potential conflicts. Many blind people are therefore unwilling, correctly, to step out and just assume that drivers will stop. A recent article discussed using critical gap time for pedestrian crossings as a more accurate measure (Koslow et al., *ITE Journal*, 2013) and is similar to Sauerburger's timing method for detection of adequate gaps in traffic (Barlow, et al. 2010, foundations of O&M chapter on teaching street crossing).

Because the sound of vehicles after they have passed the crosswalk can mask the sound of approaching vehicles, individuals who are blind may not recognize gaps for several seconds after they begin. It frequently takes three seconds or more before the noise of vehicles that have passed is diminished enough to allow detection of a following gap (Guth et al., 2013). In comparison, a sighted traveler oftentimes seizes a gap opportunity immediately after the vehicle has passed through the crosswalk (Schroeder et al., 2006).

Figure 2-2: Blind pedestrian attempting to cross at three-lane roundabout exit

This photo shows a pedestrian with long cane at three lane roundabout attempting to cross, with car crossing the crosswalk, not yielding

Although crossing one direction of traffic at a time at roundabouts can be a benefit for sighted pedestrians, the sound of traffic on the other side of the splitter island is not usually masked by the island, so traffic moving in other lanes or in the circulatory roadway can also mask the sound of approaching vehicles in the lane to be crossed. The same is true at CTLs, where the movement of vehicles in other lanes can mask the sound of closer traffic in the channelized lane, negating somewhat the safety benefits of a separated single-lane crossing for individuals who are blind.

2.2.2 Crossing When Drivers Have Yielded

Crossing when vehicles have yielded requires first detecting the vehicles, then confirming that the vehicles have stopped, and that the vehicles are staying stopped (Long et al., 2005). At roundabouts and CTLs, both the masking sounds of other traffic in the intersection and the tendency of some drivers to yield 30 feet or more upstream of the crosswalk result in yields that are not detected and used by the pedestrians who are blind (Ashmead et al., 2005; Schroeder et al., 2011). Also, drivers generally wait only a few seconds (Inman et al., 2006) before deciding that the individual is not going to cross. Oftentimes, previously yielded drivers begin to move again, just as the pedestrian has detected that the driver is present and possibly yielding. This lack of understanding resulted in some risky decisions by pedestrians in research (Schroeder et al. 2015).

The sound-masking challenge noted above for detecting gaps also can affect the use of yielded vehicles. The sound of one vehicle that has yielded just upstream of the pedestrian can mask sounds of other vehicles approaching in adjacent lanes of a multi-lane crossing. This situation is similar to the *multiple threat* pedestrian crash type that is discussed frequently in pedestrian safety literature (e.g. PEDSAFE), where a yielding vehicle in the near lane blocks the line of sight between the pedestrian and an approaching vehicle in the far lane.

2.3 Overview of Previous Research on Wayfinding by Blind Persons at Roundabouts and CTLs

While anecdotal evidence suggests that finding crosswalks, aligning to cross, and maintaining alignment while crossing at roundabouts and CTLs can cause considerable difficulty, there has been very little research specifically addressing these tasks. To our knowledge, the only previous research that has specifically focused on wayfinding at roundabouts and CTLs is pilot research conducted in Raleigh, North Carolina (Bentzen, B.L. Barlow, J.M., Guth, D., Long, R., Scott, A., Cunningham, C., & Schroeder, B., 2012).

The Raleigh pilot research documented the difficulty of locating the crosswalk for pedestrians who are blind. Participants passed the crosswalk without detecting it on 17.9% of trials, and participants aligned in a heading that would have resulted in their completing crossings within the crosswalk if they maintained that heading on only 52.1% of trials. Temporary installation of a prototype 24-inch-wide guidance surface of bar tiles extending across the width of the sidewalk, and in which the bars were aligned perpendicular to the direction of travel on the crosswalk, resulted in reduction in failure to locate the crosswalk to 2.4% of trials, and an increase in headings that would have resulted in completion of crossings within the crosswalk to 77.3% (both statistically significant).

The guidance surface used in the pilot research in Raleigh was selected because, internationally, it is common to use a tactile walking surface comprised of raised bars to both indicate the crosswalk location and guide pedestrians who are blind to crosswalks. The raised bar surface is called a “guiding pattern” in technical standards developed by the International Organization for Standards (ISO 23599:2012, Assistive products for blind and vision-impaired persons – Tactile walking surface indicators). The guiding pattern surface is not typically used in the US at this time. In other countries, the guiding pattern is usually used in association with truncated domes (also known in the US as detectable warning surfaces), which are used to warn of hazards such as drop-offs at transit platform edges, level transitions between pedestrian and vehicular ways, or changes in direction.

The guiding pattern is required to have a minimum effective width of 550 mm (21.65 in) when it is intended to be detected by a person approaching at an angle (ISO 23599). International research has determined specifications for the truncated dome and guiding patterns to ensure that they are highly detectable when used on various walking surfaces, and that they are highly discriminable from one another (Bentzen, Barlow and Tabor, 2000). That research was the basis for the ISO specifications. While there is considerable international research on the detectability of these types of surfaces, there has been little research on their use in travel or the ability of blind pedestrians to follow or align with guiding patterns effectively.

Internationally, guidance surfaces comprised of raised bars typically have the bars aligned parallel to the direction of travel (where bar tiles approximately 24-inch-wide alert travelers who are blind to the location of a crosswalk, and then guide them to the crosswalk, or to the top of the curb ramp leading to the crosswalk). In the Raleigh pilot research, the surface was used with the bars aligned perpendicular to the direction of travel so that the bars would also provide an optimal physical cue for alignment to cross the street. Research by Takeda et al. (2006) and by Scott et al. (2011a) has found that raised bars aligned perpendicular to the direction of travel provided significantly greater accuracy in alignment than raised bars aligned parallel to the direction of travel.

Accurate initial alignment, however, does not guarantee that pedestrians who are blind will maintain that alignment as they cross streets (often referred to as “maintaining a heading”). Guth and LaDuke (1995) found absolute errors (veering) from a well-aligned starting point over a distance of 25 meters, in the absence of physical or acoustic guidance cues, ranged from 1.84 to 5.75 meters, and Kallie, Schrater and Legge (2007) found a comparable range of error. This translates into a rate of error of 7-23% per meter of crossing. For a 12-foot-long, one-lane crossing, this error range translates into an error up to 2.8 feet on either side of the crosswalk.

In research to identify cues for alignment that would also result in maintaining an accurate heading across a crosswalk, Scott et al. (2011b) had participants align on a plywood “curb ramp,” and then cross a virtual street in a parking lot using five tactile or acoustic cues, including raised bars oriented perpendicular to the direction of travel on the crosswalk. Participants’ locations relative to a virtual six-foot-wide crosswalk were made at distances of 12, 36 and 72 feet from the starting curb ramp. At 12 feet, average distance from the centerline of the crosswalk showed that participants were well within the width of the crosswalk regardless of the cue. However, by 36 feet, participants were within the crosswalk only when the cue was a prototype guidestrip or guidestrips across the crosswalk or a prototype beaconing accessible pedestrian signal. The guidestrip(s) could be followed or “trailed” with the pedestrian’s long cane, and the beaconing signal provided an acoustic aiming point. The research also suggested that participants were generally not very good at aligning with the slope of the ramp itself or with detectable warnings alone without the presence of additional treatments.

On the basis of this research, it appears likely that if blind pedestrians are accurately aligned *at the center of the crosswalk* when they begin to cross at a roundabout or CTL, they will be able to maintain their heading sufficiently to still be within a six-foot-wide crosswalk if they are crossing a single lane or potentially two lanes. However, individuals often align to cross on one edge of the sidewalk or curb ramp rather than at the center. Crosswalks that are more than two lanes wide may require an additional or different tactile or acoustic cue to enable pedestrians who are blind to reliably remain within the crosswalk. A tactile guidestrip or an audible beacon, as reported by Scott et al. (2013), was more recently found to enable individuals to remain within the crosswalk at complex signalized intersections in situations where vehicular sound is minimal or where vehicles are not moving on a parallel trajectory relative to the with the crosswalk direction (Barlow et al., 2013). Based on this research, it appears that tactile guidestrips might be considered when the goal is to promote a straight line of travel within the crosswalk at roundabouts and CTLs. The challenge of traveling in a relatively straight line in the crosswalk also has implications for the design and size of channelization and splitter islands, and is discussed in later sections.

2.4 Overview of Research on Treatments to Reduce Crossing Risk for Blind Pedestrians

In order to inform the site selection and treatment evaluation, a summary of existing and prior research on treatment effectiveness on roundabout and channelized turn lane accessibility is provided below.

2.4.1 A Synthesis of Crossing Treatment Effectiveness

From the completed NCHRP 674 report, two treatments emerged that showed particular promise: the Pedestrian Hybrid Beacon (PHB, also known as a HAWK signal or HAWK beacon) and a raised pedestrian crosswalk. One of the earliest implementations of the PHB was at midblock and intersection locations in Tucson, Arizona. It was documented to have high rates in yielding (see NCHRP Report 562, Fitzpatrick et al., 2006). A temporary implementation of the PHB at a two-lane roundabout was tested in Golden, Colorado, as documented in NCHRP Report 674 (Schroeder et al., 2011a), and a permanent installation now exists at roundabout in Oakland County, Michigan with both two-lane and three-lane approaches. In NCHRP Project 3-78A, the team also tested a raised pedestrian crossing (RCP) at the same two-lane roundabout where the PHB was installed in Golden, CO.

Exhibit 1: Images of Sample Treatments

a) Lacey, WA Overhead Flashing Beacon

b) Tucson, AZ RPC at Channelized Turn lane

c) Oakland County, MI PHB three-lane RBT

d) RRFB in Olympia, WA

This exhibit shows pictures of four existing treatments including: (a) an overhead flashing beacon at a single-lane roundabout approach in Lacey, WA, (b) a raised pedestrian crosswalk at a channelized turn lane in Tucson, AZ, (c) a Pedestrian Hybrid Beacon at a three-lane roundabout approach in Oakland County, MO, and (d) a rectangular rapid-flashing beacon at a two-lane roundabout in Olympia, WA.

NCHRP 3-78A further studied a *sound strip* treatment geared at sending distinguishable audible patterns of vehicles approaching in a channelized turn lane, which would then allow a blind pedestrian to isolate the CTL vehicles from adjacent through traffic. The sound strip treatment was tested in isolation and along an overhead pedestrian-activated flashing beacon geared at promoting driver yielding. Project 3-78A further tested a variety of sites in a *no treatment* condition, which includes all "before" conditions of the tested treatments, as well as data for three single-lane roundabouts without treatments.

Since the completion of NCHRP 3-78A data collection, another treatment has emerged that is a viable consideration. The Rectangular Rapid-Flashing Beacon (RRFB) has demonstrated great potential as an effective treatment to generate high yielding rates by drivers for pedestrians. The RRFB was first implemented at midblock locations in St. Petersburg, Florida, and exhibited high, sustained vehicular yield rates (Shurbutt and Van Houten, 2010). In a response to the effectiveness of the RRFB at midblock locations, FHWA recently commissioned a 30-month study to specifically look at the viability of the RRFB as an accessibility treatment at multi-lane roundabouts (FHWA, 2011). Early results in that project suggest that an accessible crossing environment may be established by the RRFB treatment only if combined with high driver yielding and roundabout geometry that promotes low vehicle speeds. In a prior evaluation of RRFBs at a multi-lane roundabout in Oakland County, Michigan, significant accessibility challenges remained due to low driver compliance and high vehicular speeds, especially when tested at multi-lane exits.

The following tables summarize the effectiveness of the various treatments in terms of orientation and mobility (O&M) *interventions* and the *average delay* experienced by blind travelers.

Table 2-1: Summary of Results Pedestrian Hybrid Beacon. (Schroeder et al., 2011a and RCOC 2011)

City	Crossing Geometry	Entry/Exit	Study	O&M Int.	Avg. Ped. Delay (sec.)
Golden, CO	Two-Lane RBT Crossing	Entry/Exit	No Treatment*	2.4%	16.0
Golden, CO	Two-Lane RBT Crossing	Entry/Exit	With Treatment	0.0%	5.8
Oakland County, MI	Two-Lane RBT Crossing	Entry Leg	No Treatment*	1.9%	15.4
Oakland County, MI	Two-Lane RBT Crossing	Entry Leg	With Treatment	0.0%	11.5
Oakland County, MI	Two-Lane RBT Crossing	Exit Leg	No Treatment*	8.7%	19.0
Oakland County, MI	Two-Lane RBT Crossing	Exit Leg	With Treatment	1.7%	11.2
Oakland County, MI	Three-Lane RBT Crossing	Entry Leg	No Treatment*	7.7%	20.1
Oakland County, MI	Three-Lane RBT Crossing	Entry Leg	With Treatment	0.0%	14.2
Oakland County, MI	Three-Lane RBT Crossing	Exit Leg	No Treatment*	9.6%	22.3
Oakland County, MI	Three-Lane RBT Crossing	Exit Leg	With Treatment	0.8%	11.7

Table Caption: The table shows a summary of research results of various studies performed on the Pedestrian Hybrid Beacon (PHB) at multi-lane roundabouts. Rows marked with (*) correspond to the "pretest" condition, which is equivalent to a no treatment case, with only the crosswalk markings and detectable warning surfaces provided.

Table 2-2: Summary of Results RRFB. (RCOC 2011, FHWA TOPR34 Study)

City	Crossing Geometry	Entry /Exit	Study	O&M Int.+	Avg. Ped. Delay (sec.)
Oakland County, MI	Two-Lane RBT	Entry	No Treatment*	7.5%	20.8
Oakland County, MI	Two-Lane RBT	Entry	With Treatment	0.0%	17.1
Oakland County, MI	Two-Lane RBT	Exit	No Treatment*	23.8%	22.2
Oakland County, MI	Two-Lane RBT	Exit	With Treatment	16.4%	18.8
Oakland County, MI	Three-Lane RBT	Entry	No Treatment*	12.5%	35.2
Oakland County, MI	Three-Lane RBT	Entry	With Treatment	7.6%	19.8
Oakland County, MI	Three-Lane RBT	Exit	No Treatment*	23.2%	30.5
Oakland County, MI	Three-Lane RBT	Exit	With Treatment	18.9%	24.8
Olympia, WA (4th)	Two-Lane RBT	Entry	With Treatment	2.2%	4.3
Olympia, WA (4th)	Two-Lane RBT	Exit	With Treatment	3.0%	2.8
Olympia, WA (Olympic Way)	Two-Lane RBT	Entry	With Treatment	6.7%	4.5
Olympia, WA (Olympic Way)	Single-Lane RBT	Exit	With Treatment	0.0%	2.9
Olympia, WA (14th Street)	Two-Lane RBT	Entry	With Treatment	7.1%	2.3
Olympia, WA (14th Street)	Two-Lane RBT	Exit	With Treatment	2.4%	2.9
Springfield, OR (Hayden Br.)	Two-Lane RBT	Entry	With Treatment	2.2%	8.9
Springfield, OR (Hayden Br.)	Two-Lane RBT	Exit	With Treatment	12.2%	9.3
Springfield, OR (Pioneer Pkwy)	Two-Lane RBT	Entry	With Treatment	4.2%	5.7
Springfield, OR (Pioneer Pkwy)	Two-Lane RBT	Exit	With Treatment	11.4%	10.4
Oshkosh, WI (Jackson St)	Two-Lane RBT	Entry	With Treatment	2.1%	12.4
Oshkosh, WI (Jackson St)	Two-Lane RBT	Exit	With Treatment	16.0%	17.3
Oshkosh, WI (Murdock Ave)	Two-Lane RBT	Entry	With Treatment	0.0%	13.1
Oshkosh, WI (Murdock Ave)	Two-Lane RBT	Exit	With Treatment	15.0%	17.0
Carmel, IN (Clay Terrace Blvd)	Two-Lane RBT	Entry	With Treatment	3.8%	16.4
Carmel, IN (Clay Terrace Blvd)	Two-Lane RBT	Exit	With Treatment	4.0%	13.3
Albany, NY (Fuller Road North)	Two-Lane RBT	Entry	With Treatment	13.6%	9.8
Albany, NY (Fuller Road North)	Two-Lane RBT	Exit	With Treatment	21.7%	28.2
Albany, NY (Fuller Road South)	Two-Lane RBT	Entry	With Treatment	1.7%	8.5
Albany, NY (Fuller Road South)	Two-Lane RBT	Exit	With Treatment	12.9%	10.2
Davidson, NC (Griffin St - East)	Two-Lane RBT	Entry	With Treatment	4.3%	9.1
Davidson, NC (Griffin St - East)	Two-Lane RBT	Exit	With Treatment	0.0%	10.1
Davidson, NC (Griffin St - West)	Two-Lane RBT	Entry	With Treatment	0.0%	14.2
Davidson, NC (Griffin St - West)	Two-Lane RBT	Exit	Wit Treatment	8.3%	10.7

Table Caption: The table shows a summary of research results of various studies performed on the Rectangular Rapid-Flashing Beacon (RRFB) at multi-lane roundabouts. Rows marked with (*) correspond to the "pretest" condition, which is equivalent to a no treatment case, with only the crosswalk markings and detectable warning surfaces provided.

Table 2-3: Summary of Results for Other Treatments. (Schroeder et al., 2011a and RCOC 2011)

Crossing Geometry	City	Treatment	Entry/Exit	O&M Int.	Avg. Ped. Delay (sec.)
Two-Lane RBT Crossing	Golden, CO	No Treatment*	Entry/Exit	2.4%	16.0
Two-Lane RBT Crossing	Golden, CO	RPC	Entry/Exit	0.0%	5.8
CTL Crossing	Charlotte, NC	No Treatment*	n/a	9.4%	26.2
CTL Crossing	Charlotte, NC	Sound Strips	n/a	2.9%	18.5
CTL Crossing	Charlotte, NC	No Treatment*	n/a	5.6%	23.4
CTL Crossing	Charlotte, NC	SS & Beacon	n/a	1.4%	12.2
Single-Lane RBT Crossing	Raleigh, NC	No Treatment	Entry Leg	2.1%	10.5
Single-Lane RBT Crossing	Raleigh, NC	No Treatment	Exit	5.8%	11.6
Single-Lane RBT Crossing	Charlotte, NC	No Treatment	Entry Leg	0.8%	26.6
Single-Lane RBT Crossing	Charlotte, NC	No Treatment	Exit Leg	0.8%	24.0
Single-Lane RBT Crossing	Golden, CO	No Treatment	Entry Leg	2.8%	10.9
Single-Lane RBT Crossing	Golden, CO	No Treatment	Exit Leg	0.0%	13.0

Table Caption: The table shows a summary of research results of various studies performed on other treatments at multi-lane roundabouts, single-lane roundabouts, and intersections with channelized turn lanes. Rows marked with (*) correspond to the "pretest" condition, which is equivalent to a no treatment case, with only the crosswalk markings and detectable warning surfaces provided.

The results in the tables show that the PHB was effective in reducing both interventions and delay in all studied conditions. The PHB reduced the rate of interventions to zero at the Golden, CO roundabout, as well as the two-lane and three-lane entry legs at the Oakland County, MI roundabout. For the two-lane and three-lane exit legs in Oakland County, some interventions remained even in the PHB post-test condition, although at a statistically significant reduction over the pretest, where intervention rates were very high. The PHB installations also had a consistent impact on the average pedestrian delay, which was reduced in all tested installations.

In addition to the PHB evaluation, the exhibits show promise for other treatments, including the raised pedestrian crosswalk (zero post-test interventions in Golden, CO) and the rectangular rapid-flashing beacon (zero post-test interventions at two-lane entry in Oakland County, MI). However, with a limited number of studies, these results cannot be generalized at this time, and the data further point to some remaining accessibility concerns even with treatments like the RRFB (e.g. 16.4% interventions at a two-lane roundabout exit in Oakland County, MI). A large number of two-lane roundabout RRFBs is also under evaluation through a study performed for FHWA by members of this research team.

For single-lane roundabouts, all studied sites show relatively low intervention rates, although some accessibility challenges remain as evident, for example, by a 5.8% exit-leg intervention rate at the Raleigh, NC site. Other research by this team on gap judgments at a single-lane roundabout in Tampa, FL by pedestrians who are blind further supports the notion that under high-volume and high-speed conditions, single-lane roundabouts can exhibit accessibility difficulties (Guth et al., 2011).

Much less is known at the present time about ways to improve accessibility at single-lane channelized turn lanes, although research has demonstrated significant challenges. Tested treatments in NCHRP 3-78A proved only partially successful (intervention rates of 2.9% and 1.4% in post-test). While signalization may be a feasible treatment solution given existing signal controllers and power at most CTL locations, additional research on raised crosswalks and speed-reducing geometric alignment is highly desirable.

2.4.2 Opportunities Through Geometry and Geometric Treatments

In the discussion of accessibility treatments, emphasis is typically placed on technology solutions, often in the form of signalization or beaconing treatments. Sometimes overlooked is an effort to enhance accessibility through geometric treatments and modifications to the site in question. In particular, geometric treatments that encourage (a) low vehicular speed, (b) good visibility and sight distances of the crosswalk, and (c) a separation of conflict points to reduce cognitive load for drivers and pedestrians warrant further scrutiny and consideration. Research has long linked lower vehicle speeds to improved safety by increasing the opportunity to react by drivers and pedestrians and reducing the severity of collisions if they occur. Lower speeds are further demonstrated to be associated with a higher likelihood that drivers will yield, and good visibility (and no occlusion of auditory cues) intuitively facilitates driver and pedestrian reactions to the presence of the other mode. A separation of conflict points may further enhance yielding and increase driver awareness of the crosswalk and the pedestrian.

The potential of geometric design to enhance accessibility appears particularly relevant at single-lane roundabouts and channelized turn lanes, but even two-lane roundabouts may be designed with an emphasis on pedestrian access. Through studies conducted in this research and supported by earlier accessibility work, this team seeks to identify what aspects of geometry contribute to enhanced accessibility and document these findings. Examples include the R1 through R5 radii of a roundabout as described in NCHRP Report 672, the relative location of the crosswalk to the circulating lane, the shape of the splitter island at a channelized turn lane, and the curve radii in that channelized turn lane.

The potential benefits of a low-speed, pedestrian friendly environment may further be enhanced by geometric treatments like the raised pedestrian crosswalk (RPC). While any low-speed and geometric treatment needs to consider impacts on other modes at the intersection (particularly on heavy vehicles), an RPC performed mostly as well as a PHB in testing in NCHRP 3-78A at a fraction of the installation and maintenance cost.

A review of the literature on RPCs showed significant guidance on the design of RPCs through ITE's *Traffic Calming: State of the Practice* (ITE, 2012a) and an ITE Proposed Recommended Practice on *Guidelines for the Design and Application of Speed Humps* (ITE, 2012b), as well as various state and local agencies (City of San Diego, 2012; Delaware DOT, 2012). Research has further highlighted impacts on RPC design details like the vertical elevation, transition slope, and transition shape (flat, sinusoidal, or parabolic). Mohammadipour et al. even developed a speed prediction equation for RPCs as a function of these design variables (Mohammadipour et al., 2009). The authors further suggested narrowing the roadway in advance of the RPC, a practice that is reflected also in some local guidance (e.g. Placer County, PA – Pennsylvania Department of Transportation, 2012). In combination with models that predict driver yielding as a function of speed, these RPC speed prediction equations may greatly facilitate the development of guidance for RPC installation and design. Similarly, guidance in the FHWA Roundabout Guide (Rodegerdts, 2010) on predicting vehicular speed as a function of different radii may be used to make inferences about the implications on accessibility – if this research successfully identifies a clear a linkage between vehicular speed and accessibility performance measures.

2.4.3 Understanding and Mitigation of Induced Vehicle Delay

Some concern has been raised in the engineering community about additional delay incurred by vehicles at multi-lane roundabouts if a pedestrian signal (or PHB) is installed. While some pedestrian-induced delay to vehicles always occurs when pedestrians are crossing at roundabouts, research has shown that the impacts can be reduced significantly if innovative signalization schemes are used. Through a microsimulation analysis, NCHRP Report 674 (Schroeder et al., 2011a) explored these impacts in a computer modeling environment using the VISSIM software. The authors tested impacts using three signalization strategies:

1. Use of a PHB over a conventional red-yellow-green signal,
2. Implementation of a two-stage signal scheme, where a pedestrian call only stops one direction of traffic at a time, and
3. Relocation of the crosswalk to a zig-zag (offset) and distal configuration.

The authors further tested varying pedestrian and vehicle volumes, as well as single-lane and multi-lane roundabouts. For this discussion, only some of the two-lane roundabout results are presented. The table below shows the pedestrian-induced increase in average vehicle delay at the roundabout for various strategies. All strategies are also compared in terms of their percent reduction in delay relative to the assumed base case of a single-stage, green-yellow-red signal at the standard crosswalk location (20-feet from circulating lane). Exhibit 2 summarizes the key findings from the effort.

Exhibit 2: Results of Simulation Testing of Roundabout Signalization Strategies (Schroeder et al., 2011a)

Crosswalk Location	*Signal Staging*	*Signal Strategy*	*Below Capacity Scenarios - Delay per Vehicle (s)*	*Below Capacity Scenarios - % Change over Base*	*At-Capacity Scenarios - Delay per Vehicle (s)*	*At-Capacity Scenarios - % Change over Base*
Proximal	***Single-Stage***	***Signal***	*14.2*	*Base*	*68.4*	*Base*
Proximal	***Single-Stage***	***PHB***	*6.3*	*-56%*	*39.4*	*-42%*
Proximal	***Two-Stage***	***Signal***	*4.1*	*-71%*	*24.4*	*-64%*
Proximal	***Two-Stage***	***PHB***	*1.5*	*-89%*	*5.5*	*-92%*
Zig-Zag	***Two-Stage***	***Signal***	*3.9*	*-73%*	*23.4*	*-66%*
Zig-Zag	***Two-Stage***	***PHB***	*1.3*	*-91%*	*7.0*	*-90%*
Distal	***Two-Stage***	***Signal***	*2.8*	*-80%*	*5.9*	*-91%*
Distal	***Two-Stage***	***PHB***	*1.2*	*-92%*	*0.0*	*-100%*

Exhibit 2 Caption: This table shows the results of a simulation-based sensitivity analysis of different pedestrian signal strategies, including a standard pedestrian signal and a pedestrian hybrid beacon (PHB). Both strategies were tested in a single-stage application (stopping traffic long enough for pedestrians to cross entry and exit leg) and a two-stage application (stopping only entry or exit at a time). The analysis further varied between three different crosswalk locations: Proximal (20-foot distance from circulating lane), Zig-Zag (exit-leg portion of crosswalk moved to 60 feet from circle), and distal (entire crossing moved to 100 feet from circle). The results are reported as average vehicle delay (in seconds) and as the percent change of a scenario to the base case.

The results indicate that the impacts on vehicular delay can be mitigated significantly by using the PHB signalization strategy (resulting in shorter vehicle solid red times), using a two-stage signal scheme (reducing the pedestrian crossing time and thus vehicular red), and by moving the exit portion of the crosswalk further away from the circulating lane (reducing vehicle queue spill-back potential into the circulating lane).

Similar to the analysis presented above, it is critical in NCHRP 3-78B to weigh the impacts of the various accessibility treatments on vehicular traffic, as well as other modes of transportation (bikes, trucks, transit, other pedestrians) as applicable. While considering different solutions, the accessibility criterion needs to be treated as a fixed constraint to comply with ADA. But where alternatives exist, these vehicular delay considerations and impacts on other modes will be important. For example, the speed-reducing effect of a raised crosswalk is expected to add vehicular delay through an increase in vehicular headways (following gaps between vehicles) and thus a reduction in capacity. Raised crosswalks may also impact bicyclist performance and pose further difficulties for maneuverability of heavy vehicles.

2.4.4 Driver Noncompliance at Roundabout PHBs

Past research has noted driver noncompliance at roundabout PHB installations, especially at the exit legs. At both studied PHB Roundabouts (Golden, CO and Oakland County, MI), a significant percentage of drivers were observed to proceed through the solid red indication without stopping. At the Golden, CO installation, 12.6% of drivers observed during the solid red did not stop at the PHB (RCOC, 2011). Due to the relatively short duration of the solid red, the actual number of vehicles corresponded to 15 out of 119 vehicles. This behavior is a concern, as the solid red indication coincides with the pedestrian WALK indication. At the Oakland County, MI roundabout, similar behavior was observed. At the 2-lane approach, 4.6% of drivers violated the steady red at the entry leg and 12.9% at the exit leg. At the three-lane approach, the rate of noncompliance of those drivers observed during steady red was 5.6% at entry and 31.1% at the exit leg (RCOC, 2011).

No risky events (defined by O&M interventions) were observed in Golden, CO, as most study participants appeared to be able to hear the approaching, non-complying motorists. In the Oakland County, MI study, a few intervention events were observed, although these were not consistently linked to driver violation of the red signal. Regardless, the observed driver behavior at PHBs warrants further consideration.

It is unclear at the present time what factors contribute to the observed behavior. However, the generally higher observed noncompliance at the exit leg points to potential sight distance concerns for drivers exiting the roundabout, as well as the possibility that drivers are likely to be accelerating at the time they encounter the signal or PHB. At the entry, drivers tend to be decelerating and are generally on a straight approach with improved signal visibility. This hypothesis is consistent with driver yielding rates, which are generally higher at the entry leg than at the exit (e.g. Schroeder and Rouphail, 2011b; Geruschat and Hassan, 2005).

It should be noted here that at the time of the two experiments, both PHBs had been installed relatively recently, on the order of four to six weeks prior to the experiment. While this allowed for some driver adaptation time, it is unclear how many drivers were familiar with the intended operations of the PHB system because of relatively low occurrence of pedestrian activity at both roundabouts. Since the PHB rests in "dark" for vehicular traffic, it is possible that most drivers had not previously encountered the PHB in an active state. Follow-up research investigating the long-term performance of PHBs at roundabouts is therefore strongly recommended.

To further test driver compliance at multi-lane roundabout exit signals, members of this team performed a driver simulator study (Salamati et al., 2012). The authors found similar noncompliant behavior at the exit, but also that compliance improved as the signal was moved further way from the circulating lane. These findings support the sight distance and reaction time hypothesis, but more empirical work is needed to confirm these results.

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3 METHODOLOGY

This chapter summarizes the study methodology for the project. The discussion includes the field study protocols of the various components of the *Accessibility Audit*, and a discussion of site selection and prioritization of research needs that guided the experimental plan.

3.1 Data Collection Protocol

For data collection under the auspices of NCHRP 3-78B, the team applied a newly developed study protocol that was enhanced based on the lessons learned in NCHRP 3-78A and in earlier research. The A*ccessibility Audit* limits the use of human subjects to the assessment of gap and yield utilization, delay, and risk while employing other, more focused studies to assess parameters such as the propensity of drivers to yield. Project 3-78A gathered a great deal of data on crossings by human subjects, but it should be noted that there was high inter-subject variability due to differences in travelers' skill levels and tolerance for risk, along with variability among sites and treatments. The reactions of blind participants to the treatments, their ability to detect yields adequately, and driver reactions can be confounded by these differences. The Accessibility Audit carefully isolates the different accessibility indicators in a resource-efficient manner.

The proposed studies in the Accessibility Audit protocol represent those that maximize the expected results for analysis and model development while balancing resource needs. The five studies are as follows:

1. **Indicator Study with blind Participants**: Blind pedestrians standing at roundabout and CTL crosswalks made independent crossing decisions and indicated to researchers by raising their hand when they **would** cross, without actually crossing the street. These *crossing judgments* were later analyzed in regard to the speed and distance of approaching vehicles as judgments were made, and this in turn permitted the research team to quantify the degree of time-to-contact/risk inherent in the crossing judgments. The study also included the use of pre- and post-test participant questionnaires to obtain standardized feedback about the difficulty individuals experienced at various locations in making judgments, and to assess their crossing confidence. A record of vehicle volume during the indicator trials also was obtained.
2. **Wayfinding and Alignment Study with Blind Participants:** The team evaluated blind pedestrians' wayfinding behaviors as they prepared for crossings and as they actually crossed the road. In this component of the Audit, which followed the indicator study described above, the team observed participants as they attempted to independently locate crosswalks at unfamiliar locations, align for crossings, and maintain their alignment during a crossing (after being instructed by an O&M specialist that it was safe to step into the roadway. For safety purposes, they were followed closely during the study by the O&M specialist). This study allowed the research team to document the wayfinding challenges of the entire crossing (i.e., both the entry and exit at roundabouts, and at all lanes at CTLs).
3. **Yielding study:** The research team gathered data on driver yielding behavior in response to pre-defined set of pedestrian behaviors. Members of the research team, sometimes wearing dark glasses and carrying a long cane, acted as pedestrians/participants in this study. During some trials, the research team member stood near the crossing point of the target intersections (i.e., near the curb ramp) and moved the long cane or took a small step toward the street as vehicles approached. Other variables regarding pedestrian-driver interaction also were studied. Controlling pedestrian behavior allowed the research team to compare results across sites, which would have been difficult to do if blind individuals were the participants in this study.
4. **Free-flow speed study:** The speeds of free-flowing vehicles entering and exiting the roundabouts and traversing the CTLs were calculated. The goal of the study was to gain insight on the vehicle speed patterns in the vicinity of the crosswalk, and the effectiveness of various design features to reduce speeds.

5. **Site geometry audit:** The team inventoried the geometric attributes of the various study locations and compiled a photo log diary of site conditions. The geometry audit included the inscribed diameter of the roundabouts, other design parameters (e.g., radii R1-R5 per the definitions in NCHRP Report 672) of the various sites, and the crosswalk location, presence of detectable warnings, landscaping features, provisions for bicycles, and other features where applicable.

Similar in concept to a Pedestrian Road Safety Audit, the protocol was applied consistently to all sites in this study. A more detailed description of the five studies is given below.

3.1.1 Indicator Study Protocol

This portion of the audit involved the participation of five to eight blind participants at each site who were recruited for the study by the research team. Participants were familiarized with the roundabout, including the treatments designed to them in making street-crossing judgments (if any). Participants then were guided toward the crosswalk by an orientation and mobility specialist (O&M specialist). Once positioned at the curb ramp and facing the street, *they indicated* when they would cross by raising their hand, but without actually stepping into the street. These indicator trials were repeated 10 to 12 times at both the entry and the exit leg of each of two crosswalks at each roundabout (or at each tested CTL). The "indicator trial" approach was previously used in multi-lane roundabout studies in Oakland County, MI (RCOC 2011) and in Nashville, TN. (Guth et al., 2005). It is also consistent with the protocol being used in recently-completed FHWA research on the effectiveness of Rectangular Rapid-Flashing Beacons (RRFB) at multi-lane roundabouts. The "indicator only" protocol is faster than a crossing study, and most importantly, less risky for participants, drivers and researchers alike.

While data collection with participants with vision impairments is intensive and time-consuming, it is essential to making decisions about appropriate treatments to support safe and efficient pedestrian access. To streamline data collection, the team focused on the evaluation of pedestrian behavior after treatments were installed at the various crosswalks, rather than conducting traditional "before-and-after" treatment evaluations. The team was able to use data gathered in prior research as baseline information for the studies reported here, which allowed for streamlined data collection. For example, the team combined the information gathered in indicator trials with information on driver yielding behavior gathered in the naturalistic yielding studies and other studies.

During each trial, the O&M specialist evaluated the safety of the crossing decisions by showing a hand signal to a computer operator to indicate whether the crossing decision likely would have resulted in an intervention if actual crossings had been initiated by the participant. It is these "risky crossings" that were quantified and evaluated for each site. Frequency of intervention was the primary safety measure used in previous crossing studies in Nashville and Tampa, FL and other studies, where the O&M specialist physically "intervened" by stopping the pedestrian. The indicator protocol used here assigns one of three categories to each crossing event: "no intervention," "possible intervention," and "expected intervention." In addition to the O&M specialist, a second expert observer rated each crossing event as safe, possible intervention, or expected intervention, independent of the O&M specialist. These two independent risk indicators were later compared to arrive at an overall risk assessment of the crossing decision. All trials were videotaped so they can be further evaluated against more objective risk measures, such as the vehicle time-to-collision between the pedestrian decision and the arrival of the next vehicle at the crosswalk.

The team is sensitive that any research involving human subjects needs to protect the safety, privacy, and well-being of the study participants. As was done in previous research, the team obtained Institutional Review Board (IRB) approval (from North Carolina State University and the National Academy of Sciences) for all components of the Accessibility Audit, but with special emphasis on this crossing indicator study. After review by both IRBs, the team was authorized to proceed with this research protocol.

3.1.2 Wayfinding and Alignment Study Protocol

To determine if a crossing is usable by individuals who are blind or visually impaired, it is important to evaluate all the accessibility challenges, not just the determining-when-to-cross problem. Once the sites were selected for the indicator studies, the team selected a subset of these sites for the wayfinding studies. Site selections were based on maximizing the design diversity while considering the experimental and practical constraints imposed by the logistical aspects and budget constraints of the project. The wayfinding protocol required about 45 minutes of additional time per participant per site beyond that required for the crossing indicator study.

The procedure was similar to the method used in previous wayfinding research in Raleigh (Scott et. al, 2014). After the crossing indicator trials, a short break for water and snacks, and completion of the debrief for the indicator trials, participants were asked to independently approach several crosswalks two or three times at the roundabout or CTL from either upstream or downstream direction (depends on configuration of crosswalks at the roundabout or CTL and availability of landscaping or other cues or no cues at various crosswalks at the location). Instructions to participants were to find the crosswalk and align to cross and to inform the O&M specialist when he or she had done so. Performance measures for this study include:

- Time from a marked location a consistent distance from the pushbutton or crosswalk to being ready to cross;
- Location within or outside crosswalk, toward or away from circulatory roadway or downstream roadway;
- Alignment (heading) aimed within, outside crosswalk lines, toward or away from circulatory roadway or downstream roadway; and
- If pushbutton, time to find pushbutton.

After this initial alignment activity, additional measures of “maintaining heading while crossing” were gathered by having the orientation and mobility specialist tell the participant when to cross. As the crossing took place, the experimenters recorded the participant’s crossing heading accuracy. Participants also crossed to the island and aligned to cross the other roadway lanes. This gave the team information about wayfinding in relation to the configuration and features of splitter islands and triangular islands at roundabouts and CTLs.

3.1.3 Yielding Study Protocol

Since an increase in the propensity of drivers to yield is likely to provide more crossing opportunities for pedestrians who are blind, this study is a critical component of the Accessibility Audit. If drivers in all lanes routinely stop for pedestrians, as is seen in some European countries, more crossing opportunities exist. While yielding studies can be purely observational, varying pedestrian volumes across sites and different pedestrian populations are likely to introduce bias when comparing the same treatment across various roundabouts.

The study applied a protocol where a member of the research team approaches the crosswalk at random intervals (e.g. once per minute), and takes one step into the crosswalk, which is in accordance with most states’ yielding laws. A video camera and synchronized radar speed measurement system capture the position and speed of approaching vehicles, while a trained observer records the yield outcome. That observer further describes attributes of the interaction between pedestrians and driver including crossing leg (entry/exit), lane position (near/far), platooning (yes/no), vehicle type (truck/car), and others. The yield trials are performed in randomized order starting at either the entry or the exit leg. Half the trials further employ the use of a white long cane to simulate the arrival of a blind pedestrian and to test for an increased propensity of drivers to yield. In all trials, the pedestrian will take one step “into” the crosswalk in accordance with most states’ yielding laws.

The protocol is consistent with the evaluation protocol used in HRT-10-043 (FHWA 2010) and with many state laws on driver yielding ("in" vs. "at" the crosswalk). The "in" crosswalk yield results will be a direct comparison to the indicator studies, which have to be performed "at" the crosswalk to pass IRB muster. The team used the same threshold for determining whether or not drivers "would have been able to stop" using the ITE Signal Formula (ITE 2009) that was used in prior research.

3.1.4 Free-Flow Speed Study Protocol

The research team conducted a vehicle speed study at the crosswalk when no pedestrians were present, consistent with methods described in the ITE Manual of Transportation Studies (ITE, 2010). This provided insight on the relationship between geometric parameters and actual crosswalk speeds (rather than those estimated from equations in for example the FHWA Roundabout Guide). Vehicular speeds are critically linked to injury severity in the case of a pedestrian-vehicle collision, but also have a strong impact on pedestrian and driver decision-making. Higher speeds are generally associated with shorter allowable reaction times for gap crossings and have been linked to a lower likelihood of driver yielding. It was hypothesized that geometric parameters of the roundabout that impact speed therefore have a key impact on accessibility.

3.1.5 Geometry Audit Protocol

A team of trained observers documented critical geometric features of the roundabout including inscribed diameter, roundabout design radii R1-5, the crosswalk locations relative to the circulating lane, the presence and orientation of truncated dome detectable warnings, landscaping, and other factors. The documentation was in the form of a detailed and narrated photo diary of the site with special emphasis placed on features that have been linked through prior research to impacting accessibility. The objective of the geometry audit was to identify good and poor design aspects that may impact accessibility. The comprehensive results of all geometry audits and photo diaries will be a useful resource for practitioners.

3.2 Site Selection

The site selection process was principally motivated to fill knowledge gaps identified by the research team. The site selection processes balanced two competing objectives:

- The first objective was to study a broad range of treatments and combinations of treatments in order to gain insight in the accessibility performance across a range of conditions. Note that the term "treatment" in this case may also refer to geometric variations, rather than a technology solution per se.
- The second objective was to obtain a sufficient sample size for model development. While a broad range of treatment is desirable, a statistically-robust sample of any one treatment is also highly desirable. As such, it was advantageous to perform multiple studies of the same treatment (e.g. RRFB), than covering a wider range of treatments (e.g. RRFB, standard beacon, overhead beacon, in-pavement beacon, etc.).

Both objectives were considered in identifying a list of potential sites for data collection in Phase II of this project. As such, the team initially identified desirable site characteristics, which were then matched against the database inventory of available sites for a list of proposed locations.

Other considerations played into the final site selection process as well, including proximity to the research team (to save on travel expenses for sites within driving distance), and, more importantly, the ability to economize data collection at multiple sites within the same trip. When weighing studies of different treatments, the team considered the following items:

- Prior research, with a higher priority for treatments without extensive prior research;

- Treatment cost, with a higher priority for treatments with low capital cost;
- Likelihood of success, with a higher priority to treatments that are likely to have a high benefit to accessibility; and
- Boundary conditions, with a higher priority to treatments and sites that are expected to provide better insights on the boundary conditions between accessible and non-accessible.

When weighing studies in support of different models the team considered the following items:

- Expected impact, with a higher priority to models that are expected to have a key impact on accessibility (e.g. yield prediction, which has been linked to better accessibility);
- Likelihood of success, with a higher priority to models for which the team anticipates being able to obtain adequate sample sizes for modeling, under consideration also of existing data and in light of inherent variability in decision-making (e.g. gap selection is expected to show clear correlation with crossing width and approach speeds); and
- Sensitivity, with a higher priority to models expected to show high sensitivity to parameters within the realm of control of the designer (e.g. speed prediction as a function of design radii).

In general, sites were selected based on the type of crossing treatment installed. While wayfinding features were important considerations of this project, the team proposed to evaluate most wayfinding accommodations "as is." Even without explicitly screening sites for wayfinding treatments, the team was able to obtain a broad sample of landscaping treatments and accommodations from the selected sites.

3.2.1 National Agency Outreach and Site Inventory

The focus of this task was to perform a national outreach to transportation agencies with the goal of identifying existing sites with one or more treatments installed. At the same time, the team planned to identify potential locations of new installations if the list of existing treatments shows gaps for particular treatments that are identified as key research needs.

An important starting point for the identification of additional sites was the inventory database of roundabouts across the United States maintained by Kittelson and Associates, Inc. (http://roundabouts.kittelson.com/). As part of a prior research effort, the team recently amended that database to include specific information about crosswalk geometry, roundabout design speed, and other site characteristics pertinent to this project. Unfortunately, a similar database does not exist for channelized turn lanes, but these intersections are also more frequently found across the country.

The team performed additional outreach efforts in the form of an online survey. The survey was administered to national list serves (e.g. the list serve of the TRB Roundabout Committee, TRB Pedestrian Committee, ITE Traffic Engineering Council, Associate for Pedestrian and Bicycle Professionals, etc.).

Through this survey effort, combined with sites already familiar to the team, a list of 53 potential sites was identified for consideration in the data collection phase. These sites are comprised of 24 channelized turn lane sites, 22 multi-lane roundabouts, and 9 single-lane roundabouts. Of these sites, 22 have previously been evaluated in studies conducted under NCHRP 3-78a, the NIH grant, TOPR34, or other studies.

- For the 24 CTL sites, 11 have raised crosswalks, 6 have signals, 1 has an RRFB (CTL at a RBT), 1 is outfitted with a flashing beacon, and 1 has a stop sign prior to the crosswalk
- For the 22 multi-lane roundabout sites, 4 have raised crosswalks (one also a PHB), 5 have signals or a PHB, 9 have RRFBs, 1 has an offset crosswalk, and 1 has speed humps prior to the crosswalk at the entry leg
- For the 9 single-lane roundabout sites, 2 have raised crosswalks, and 1 has an RRFB

Tables with site details are shown below.

Table 3-1: CTL Sites

ID	Type	St1	St.2	City	State	No. Lanes	Treatment	Studied Before	Prior Project
1	CTL	N Wilmot Rd	E. Speedway Bvld	Tucson	AZ	1	Stop Sign at CTL	No	n/a
2	CTL	E Mann Ave	E Gold Links Rd	Tucson	AZ	1	Large Islands	No	n/a
3	CTL	East River Rd	N/ Sabino Canyon Rd	Tucson	AZ	2	Signal	No	n/a
4	CTL	N/ Craycroft Rd	East River Rd	Tucson	AZ	1	Signal	No	n/a
5	CTL	Grant Rd	Campbell Ave	Tucson	AZ	1	RCW	No	n/a
6	CTL	Camino Seco	Wrightstown Blvd	Tucson	AZ	1	RCW	No	n/a
7	CTL	Oracle Rd	Grant Rd	Tucson	AZ	1	RCW	No	n/a
8	CTL	Lee Hill Dr	28th St	Boulder	CO	1	Skewed 3-legged	No	n/a
9	CTL	Jay Rd	Denver Boulder Turnpike (28th)	Boulder	CO	1	Skewed 4-legged	No	n/a
10	CTL	28th St	Diagonal Hwy	Boulder	CO	1	RCW- x4	No	n/a
11	CTL	28th St	Valmont Rd	Boulder	CO	1	RCW-x1	No	n/a
12	CTL	28th St	Pearl St	Boulder	CO	1	RCW- x3	No	n/a
13	CTL	28th St	walnut St	Boulder	CO	1	RCW-x2	No	n/a
14	CTL	28th St	Canyon Rd	Boulder	CO	1	RCW-x3, 1 without	No	n/a
15	CTL	27th Way	Baseline Rd	Boulder	CO	1	RCW-x1, 2without, 1 two-lane Signalized	No	n/a
16	CTL	27th Way	Broadway	Boulder	CO	1	1 without RCW	No	n/a
17	CTL	Magnolia Dr	Park Ave	Tallahassee	FL	1	Signal	No	n/a
18	CTL	St Francis Cir	W Portal Ave	San Francisco	CA	1	RCW	No	n/a
19	CTL	Grand Ave	Harrison St	Oakland	CA	1	Signal	No	n/a
20	CTL	SW Taylors Ferry Rd	SW Terwilliger	Portland	OR	1	Signal	No	n/a
21	CTL	Providence Rd	NC51	Charlotte	NC	1	Beacon	Yes	3-78a
22	CTL	Hillsborough St	Gorman St	Raleigh	NC	1	n/a	Yes	NIH
23	CTL	SE Cary Pkwy	Walnut St	Cary	NC	1	n/a	Yes	NIH
24	CTL at RBT	Fuller Rd	Washington Ave	Albany	NY	1	RRFB	Yes	FHWA

Table 3-2: Multi-Lane RBT Sites

ID	Type	St1	St.2	City	State	No. Lanes	Treatment	Studied Before	Prior Project
25	Multi-RBT	Golden Rd	Johnson	Golden	CO	2	PHB 1, RCW 1	Yes	n/a
26	Multi-RBT	Golden Rd	Ford	Golden	CO	2	RCW 1	No	n/a
27	Multi-RBT	E Orange Ave	Jim Lee Rd	Tallahassee	FL	2	Offset CW	No	NIH
28	Multi-RBT	N 40th St	E Hanna Ave	Tampa	FL	2	Low-Speed	No	n/a
29	Multi-RBT	N 40th St	E Yukon St	Tampa	FL	2	Low-Speed	No	n/a
30	Mulit-RBT	MLK Jr Blvd	N Central Ave	Kissimmee	FL	2	Entry Speed Humps	Yes	NIH
31	Multi-RBT	Causeway Blvd	Mandalay	Clearwater	FL	2	Signal, Offset CW	No	n/a
32	Multi-RBT	Clay Terrace Blvd		Carmel	IN	2	RRFB	Yes	FHWA
33	Multi-RBT	Maple Rd	Drake Rd	West Bloomfield	MI	2/3	PHB	Yes	NIH
34	Multi-RBT	Maple Rd	Farmington Rd	West Bloomfield	MI	2/3	RRFB	Yes	NIH
35	Multi-RBT	Jetton St	Griffith St	Davidson	NC	2	RRFB*	Yes	FHWA
36	Multi-RBT	Harbour Place	Griffith St	Davidson	NC	2	RRFB*	Yes	FHWA
37	Multi-RBT	Fuller Rd	Washington Ave	Albany	NY	2	RRFB	Yes	FHWA
38	Multi-RBT	Pioneer Pkwy	Hayden Bridge Way	Springfield	OR	2	RRFB	Yes	FHWA
39	Multi-RBT	Blvd des Allimettieres	Blvd St. Joseph	Gatineau	QC	2	Signal 1, Beacons 3	No	n/a
40	Multi-RBT	Blvd des Allimettieres	Rue Demontingy	Gatineau	QC	2	Signal 1, Beacons 3	No	n/a
41	Multi-RBT	Aldrich St	Mueller Blvd	Austin	TX	2	PHB and/or RCW*	No	n/a
42	Multi-RBT	4th Ave	Olympic St	Olympia	WA	2	RRFB	Yes	FHWA
43	Multi-RBT	14th Ave	Jefferson St	Olympia	WA	2	RRFB	Yes	FHWA
44	Multi-RBT	Longview Circle		Longview	WA	2	RCW	No	n/a
45	Multi-RBT	Jackson St	Murdock Ave	Oshkosh	WI	2	RRFB	Yes	FHWA
46	Multi-RBT	River Park Dr	Driveway	Riverdale	UT	2	RCW	Yes	NIH

** Treatments at this site have not been installed yet, but coordination is ongoing*

Table 3-3: Single-Lane RBT Sites

ID	Type	St1	St.2	City	State	No. Lanes	Treatment	Studied Before	Prior Study
47	Single RBT	Golden Rd	Ulysess Rd	Golden	CO	1	n/a	Yes	3-78a
48	Single RBT	Gulf Dr S	Bridge St	Bradenton Beach	FL	1	n/a	No	n/a
49	Single RBT	W. County Club Dr.	North Blvd	Tampa	FL	1	n/a	Yes	n/a
50	Single RBT	Pikea Ave	Liloa Dr	Kihei	HI	1	RRFB	No	n/a
51	Single RBT	Cherrywood Ln.	Metro Access Dr	Greenbelt	MD	1/2	RCW	No	n/a
52	Single RBT	Tienken Rd	Sheldon Rd	Rochester Hills	MI	1	RCW	No	n/a
53	Single RBT	9th St	Davidson St	Charlotte	NC	1	n/a	Yes	3-78a
54	Single RBT	Pullen Rd	Stinson Drive	Raleigh	NC	1	n/a	Yes	NIH
55	Single RBT	River Park Dr	900 W	Riverdale	UT	1	RCW	Yes	NIH

3.2.2 Overview of Studied Channelized Turn Lane Sites

Through the process of identifying research needs for CTLs, combined with an inventory of CTL treatments across the U.S., the team conducted two clustered studies of CTL accessibility in two locations across the US, supplemented by two additional isolated locations. The motivation for the clustered approach is two-fold: (1) clustering of data collection allows the team to efficiently study several sites within the same trip and (2) clustering allows the team to control for pedestrian and driver behavior by testing the same participants interacting with the same driver population for multiple sites. Prior research on roundabout accessibility, specifically the FHWA evaluation of RRFBs at multi-lane roundabouts, showed that regional differences of driver behavior appear to contribute greatly to differences across sites, making it harder to isolate the effects of geometric differences between sites. Similarly, one of the main conclusions in NCHRP Report 674 was that the blind travelers involved in the field studies had a high degree of inter-participant variability, once again making it difficult to isolate differences across sites.

The clustered approach controls for differences in driver behavior and pedestrian skill level by having the same participants cross at multiple locations in the same city. A drawback of this approach is that studies are more time-consuming per participant (accounting for travel between sites and overall more trials per participant). Another drawback is that, by spending more time at one location, fewer overall cities can be visited, while more sites can be included.

From the inventory of CTL locations, the team identified clustered sites in two cities: Boulder, CO and Tucson, AZ. Both locations offer a host of channelized turn lane locations and, more importantly, offer a range of geometric configurations and treatments at these CTLs. For example, each city has at least some CTLs with a raised crosswalk, and Tucson has signalized CTLs. Both cities are also known for embracing innovative pedestrian treatments, including pedestrian hybrid beacons and RRFBs at midblock locations, which suggests that drivers in both locations are used to seeing “special” pedestrian accommodations.

In addition, the team was able to study a CTL each in Cary, NC and Greenbelt, MD as part of a planned roundabout data collection trip. In total, 12 CTLs were studied in this research as shown in the table below. A summary of all sites is given in the following sections.

Table 3-4: Listing of CTL Study Locations

Site	Location	Type	Treatment
Wilmont at Speedway NW	Tucson, AZ	CTL	Decel Lane, Stop Sign
Sabino Canyon at Tanque Verde NE	Tucson, AZ	CTL	Decel & Accel Lane
Grant at Oracle NE	Tucson, AZ	CTL	Decel, Raised CW, Yield
Grant at Oracle SW	Tucson, AZ	CTL	Decel, Raised CW, Yield
Foothills at Baseline NE	Boulder, CO	CTL	Decel & Accel Lane
Foothills at Baseline NE	Boulder, CO	CTL	Decel & Accel, Sound Strips
Foothills at Arapahoe SW	Boulder, CO	CTL	Decel & Accel, Raised CW
28th at Pearl NE	Boulder, CO	CTL	Decel Lane, Yield
28th at Pearl NW	Boulder, CO	CTL	Yield, Raised CW
28th at Canyon SW	Boulder, CO	CTL	Decel Lane, Yield, Raised CW
Kenilworth at E. Street NW	Greenbelt, MD	CTL	Decel & Accel Lane
Kildaire Farm at Tryon SW	Cary, NC	CTL	Decel Lane, Yield

3.2.2.1 Tucson, AZ

In April 2014, the team completed data collection at four CTL locations in Tucson, AZ. All four CTLs featured different geometric and treatment combinations, as described below with aerial views of all four locations.

1. Wilmont Road at Speedway Boulevard – Northwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, stop sign at downstream merge point
2. Sabino Canyon Road at Tanque Verde Road – Northeast quadrant of intersection, urban location, deceleration and acceleration lane, no additional treatments
3. Grant Road at Oracle Road – Northeast quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk
4. Grant Road at Oracle Road – Southwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk

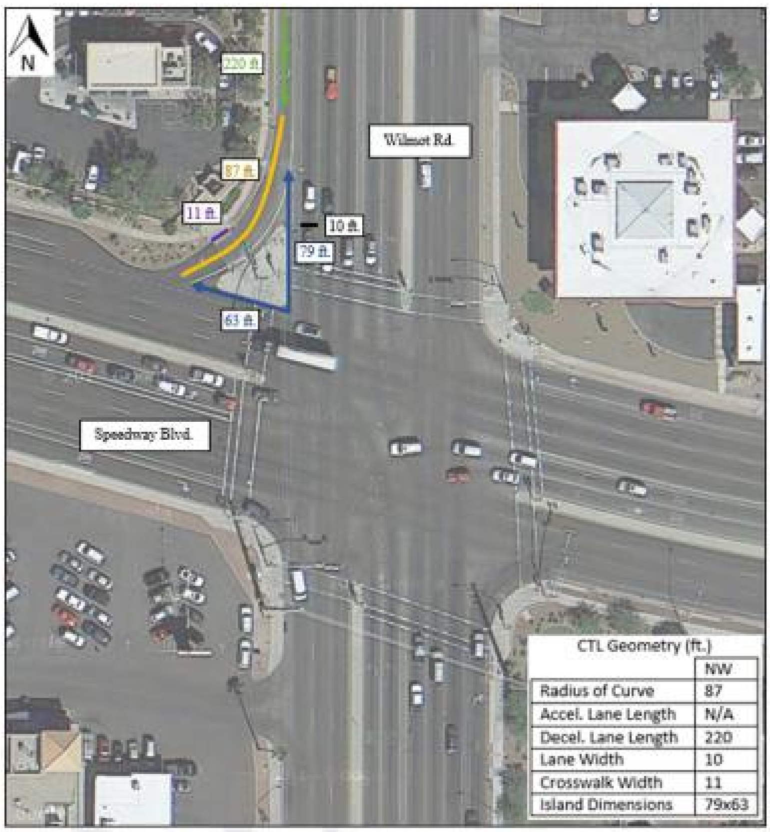


Figure 3-1: CTL at Wilmont Road at Speedway Boulevard, Tucson, AZ

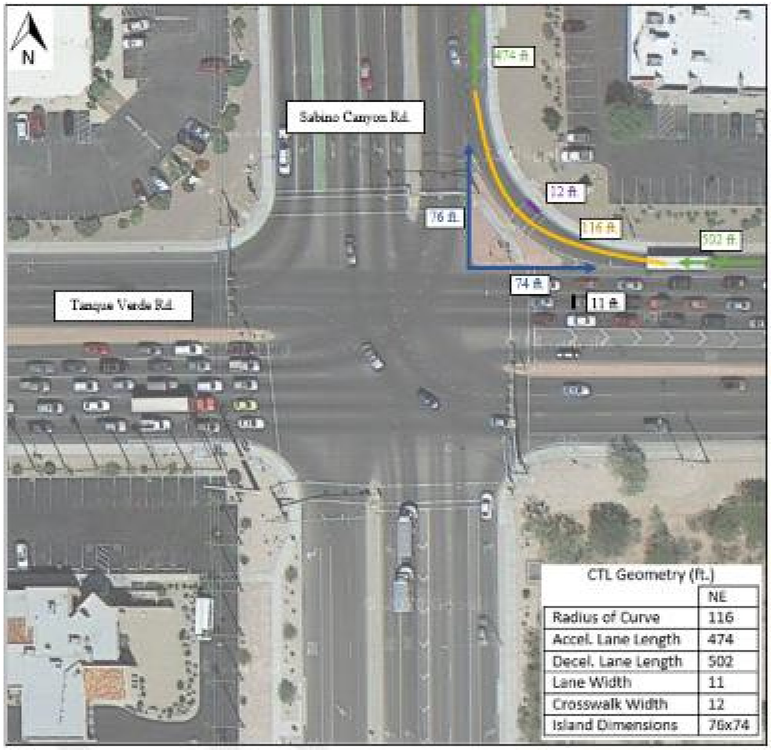


Figure 3-2: CTL at Sabino Canyon Road at Tanque Verde Road, Tucson, AZ

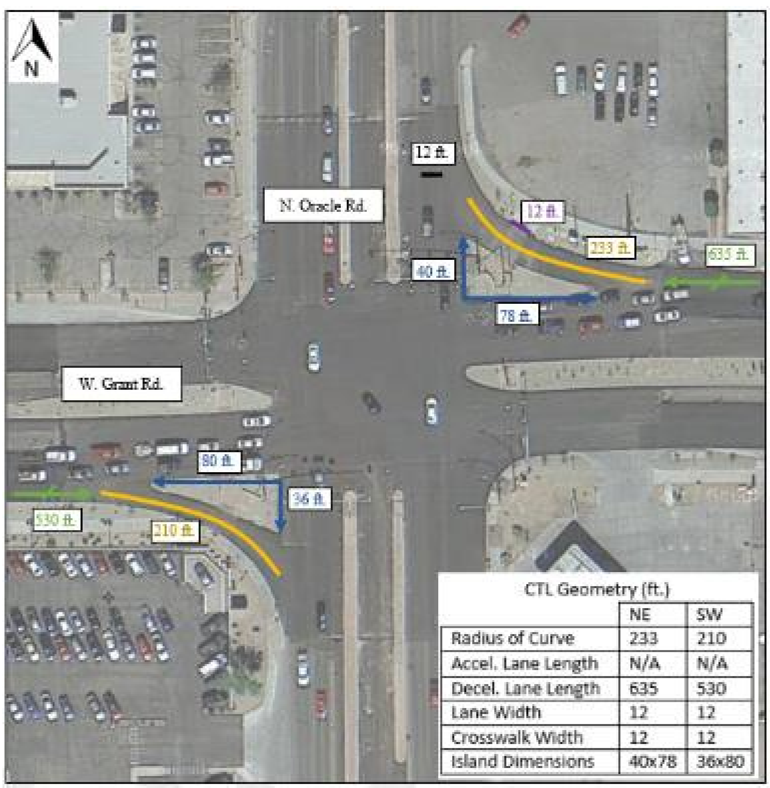


Figure 3-3: CTLs at Oracle Road and Grant Road, Tucson, AZ

3.2.2.2 Boulder, CO

In July 2014, the team completed data collection at six CTL locations in Boulder, CO. The study focused on three CTLs in an urban environment within the Boulder City Limits, as well as three CTLs under county jurisdiction. All four CTLs featured different geometric and treatment combinations as described below and accompanied by aerial views of all six locations:

1. 28th Street at Pearl Street – Northeast quadrant of intersection, urban location, deceleration lane, no acceleration lane, no additional treatments
2. 28th Street at Pearl Street – Northwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk
3. 28th Street at Canyon Boulevard – Southwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk
4. Foothills Parkway at Arapahoe Avenue – Southwest quadrant of intersection, suburban location, deceleration lane, acceleration lane, raised crosswalk
5. Foothills Parkway at Baseline Drive – Southwest quadrant of intersection, suburban location, deceleration lane, acceleration lane, sound strip treatment
6. Foothills Parkway at Baseline Drive – Northeast quadrant of intersection, suburban location, deceleration lane, acceleration lane, raised crosswalk

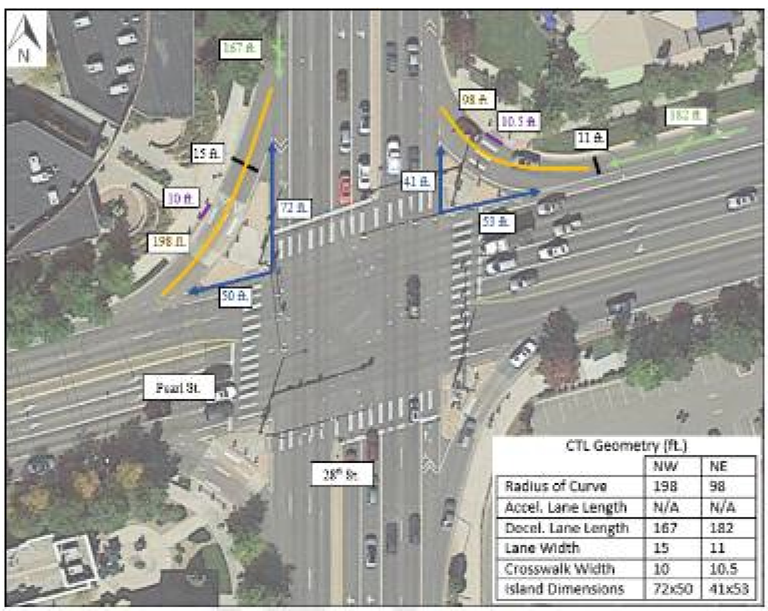


Figure 3-4: CTLs at 28th Street and Pearl, Boulder, CO

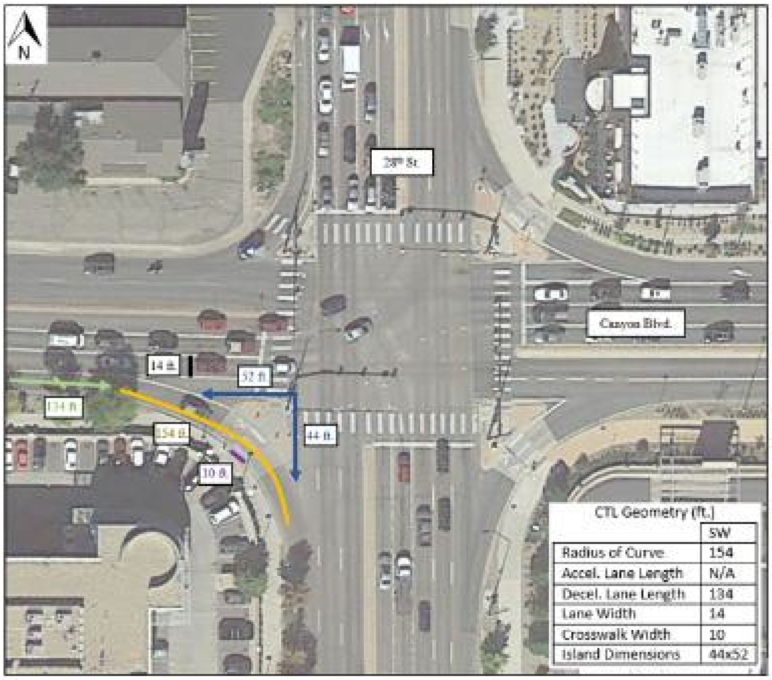


Figure 3-5: CTL at 28th Street and Canyon Boulevard, Boulder, CO

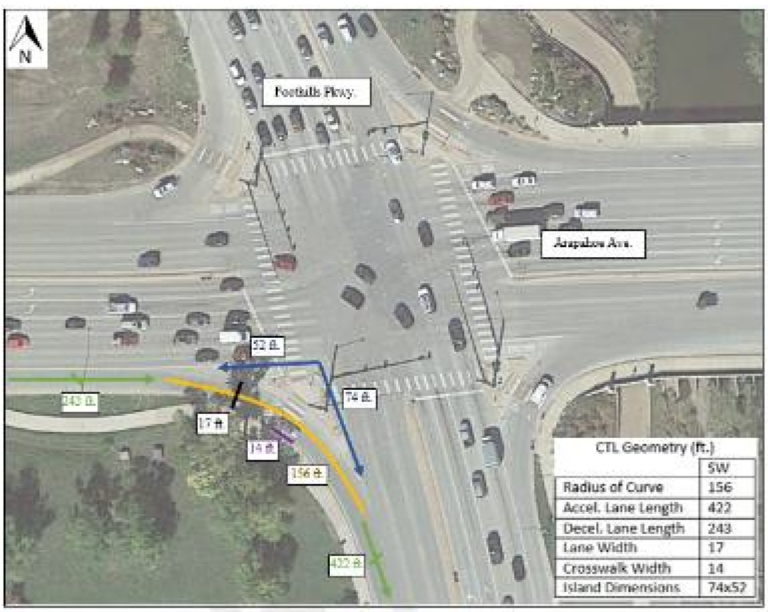


Figure 3-6: CTL at Foothills Parkway and Arapahoe Avenue, Boulder, CO

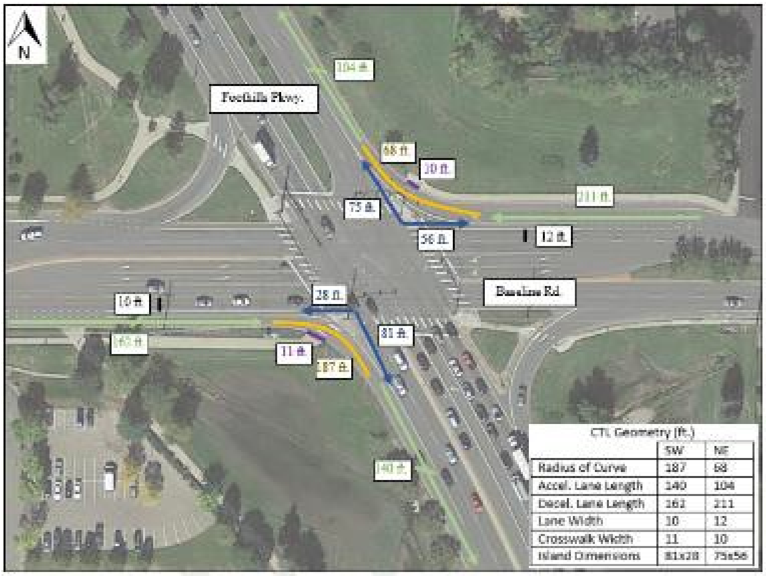


Figure 3-7: CTL at Foothills Parkway and Baseline Road, Boulder, CO

3.2.2.3 Greenbelt, MD and Cary, NC

In September 2014, the team completed data collection at a channelized turn lane in Greenbelt, MD. In November 2014, the team collected data at a CTL in Cary, NC. The sites are described below and accompanied by a series of aerial views.

1. Kenilworth Avenue at East West Highway – Northwest quadrant of intersection, deceleration lane, no acceleration lane, no other treatments installed
2. Kildaire Farm Road at Tryon Road – Southwest quadrant of intersection, deceleration lane, no acceleration lane, no other treatments installed

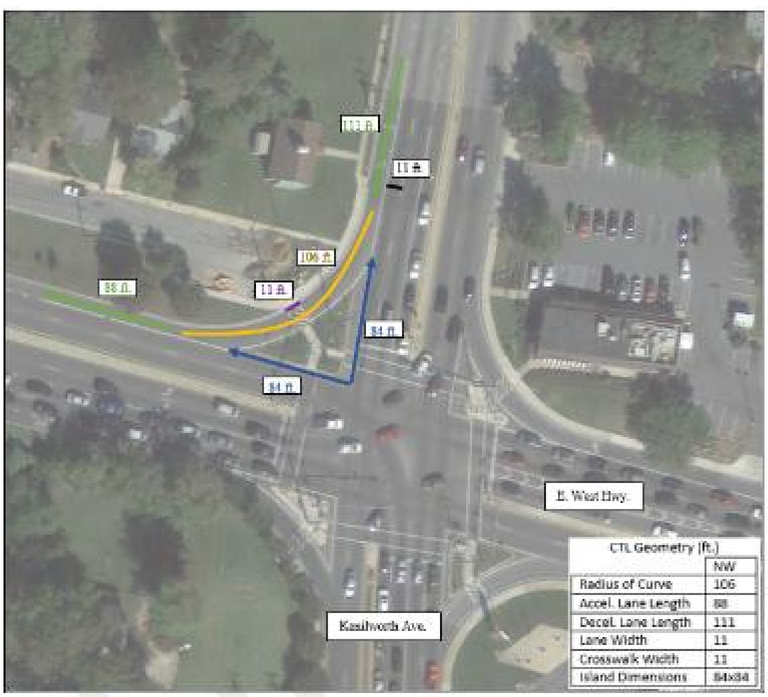


Figure 3-8: CTL at Kenilworth Avenue and East West Highway, Greenbelt, MD

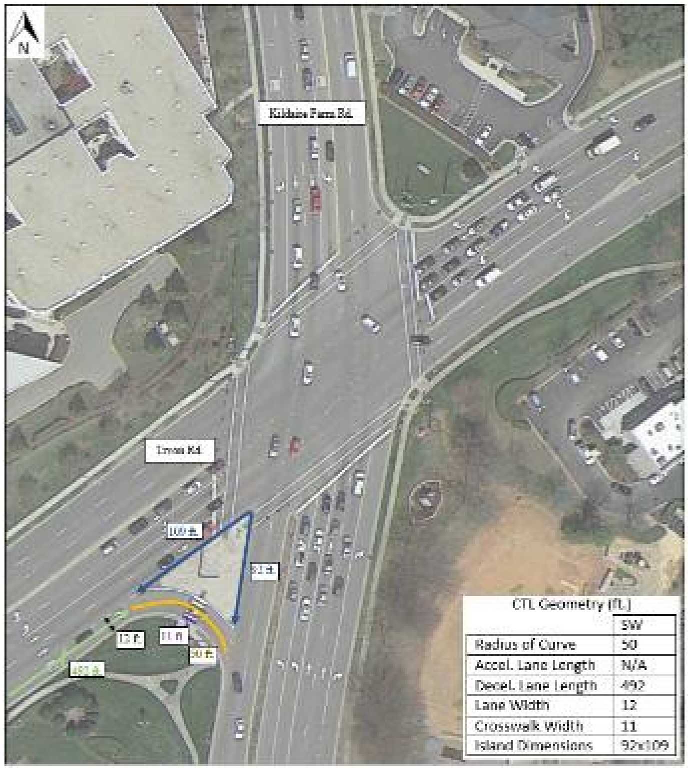


Figure 3-9: CTL at Kildaire Farm Road and Tryon Road, Cary, NC

3.2.3 Overview of Studied Roundabout Sites

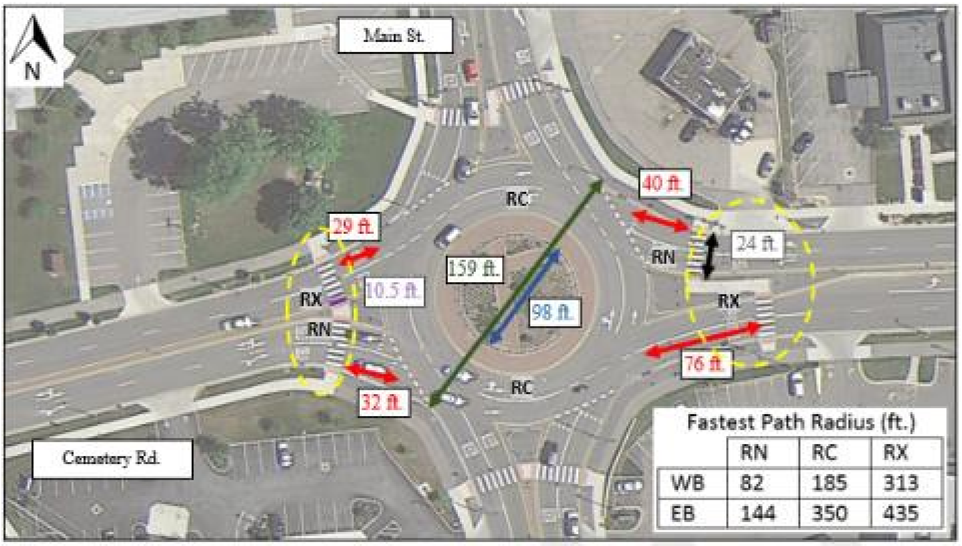
The team collected data at a total of eight roundabout approaches at five roundabouts in four different states. The emphasis in the roundabout data collection was on the evaluation of treatments not previously evaluated in sufficient detail. These treatments include: (1) raised crosswalks, (2) raised crosswalk in combination with RRFBs, and (3) rumble strips in advance of the crosswalk. The summary of sites is provided in the table below, and accompanied by aerial views and a discussion in the subsequent sections.

Table 3-5: Summary of Roundabout Study Locations

Site	Location	Type	Treatment
Cemetery at Main St. - East	Hilliard, OH	2-lane	Exit Offset Crosswalk
Cemetery at Main St. - West	Hilliard, OH	2-lane	Standard Crosswalk
Maple at Farmington - East	West Bloomfield, MI	3-lane	Raised CW and RRFB
Maple at Farmington - N/S	West Bloomfield, MI	2-lane	Raised CW and RRFB
Cherrywood at Metro - West	Greenbelt, MD	1/2 lane	Raised CW, divided lanes
State at Ellsworth - West	Ann Arbor, MI	2-lane	Rumble Strips, Exit offset CW
Huron at Nixon - South	Ann Arbor, MI	1-lane	Rumble Strips
Old Apex at Chatham - West	Cary, NC	1-lane	Standard CW, 3-legged

3.2.3.1 Hilliard, Ohio

The team completed a study at a multi-lane roundabout in Hilliard, Ohio in May 2014. The study focused on the east and west approaches of the roundabout at Main Street and Cemetery Road. Both approaches featured two-lane entries and two-lane exits. The west approach featured a “standard” crosswalk location, while the east approach showed an offset or "zig-zag" configuration. Both approaches had in-road yield to pedestrian signs installed.



Fastest Path Radius (ft.)			
	RN	RC	RX
WB	82	185	313
EB	144	350	435

Figure 3-10: Roundabout at Cemetery Road and Main Street, Hilliard, OH

3.2.3.2 Oakland County, Michigan

In August 2014, the team completed a study at the multi-lane roundabout at Maple Road and Farmington Road in Oakland County, MI. The roundabout was previously evaluated in a separate research project in (a) a "before" condition without treatment and in (b) an "after" condition with Rectangular Rapid-Flashing Beacons (RRFBs) installed. For this study, the roundabout was also outfitted with raised crosswalks at four test legs: 3-lane entry from east, 3-lane exit to east, 2-lane entry from south, and 2-lane exit to north.

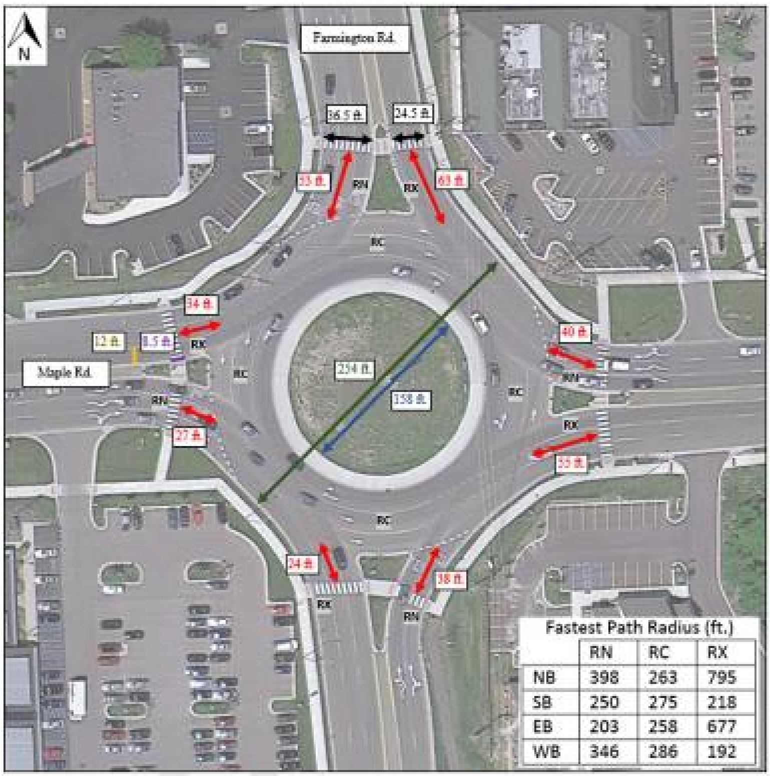
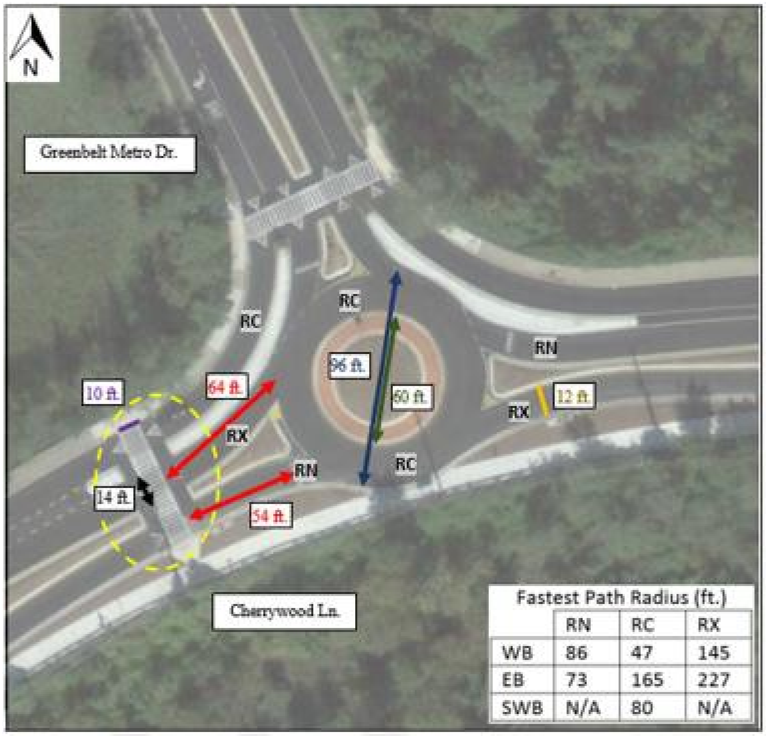


Figure 3-11: Roundabout at Maple Road at Farmington Road, Oakland County, MI

3.2.3.3 Greenbelt, MD

In September 2014, the team completed data collection at a roundabout with raised crosswalks. The roundabout was located at Cherrywood Lane at Metro Access Parkway, and it featured slip lanes and raised crosswalks. The team studied the entry and exit legs at the west approach.



	RN	RC	RX
WB	86	47	145
EB	73	165	227
SWB	N/A	80	N/A

Figure 3-12: Roundabout at Cherrywood Lane at Metro Access Parkway, Greenbelt, MD

3.2.3.4 Ann Arbor, MI

The team studied two roundabouts in Ann Arbor, MI in October 2014. The study focused on one single-lane and one two-lane roundabout, and both featured similar treatments. The sites have a milled rumble strip treatment, as opposed to a raised sound strip treatment, such as the one used at one of the CTL study locations in Boulder, CO.

The single-lane site is at Huron Parkway and Nixon Road. The site has single-lane approaches on all four legs and standard crosswalks approximately 20 feet from the circulatory roadway. A set of four rumble strips is milled approximately 50 feet prior to each crosswalk to alert drivers and provide an auditory cue for pedestrians.

The two-lane site is at State Street and Ellsworth Road. The site is a true two-lane roundabout with an offset-left design (i.e. higher deflection at entry and relatively straight exits). The crosswalks at this location are staggered (zig-zag), with the exit leg moved approximately 40 feet further away from the circle. State Road has a speed limit of 35mph and a daily volume of 31,500 vpd north of the intersection and 17,600 vpd south of the intersection. Ellsworth Road has a speed limit of 45 mph and a daily traffic volume of 15,600 vpd east and 13,000 vpd west of intersection.

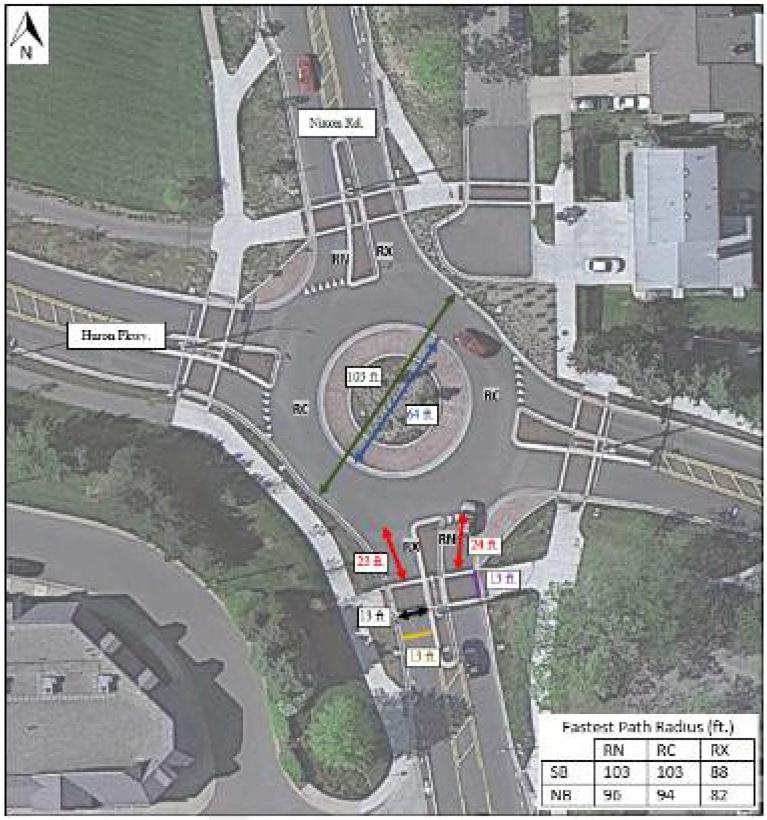


Figure 3-13: Single-Lane Roundabout in Ann Arbor, MI with Milled Rumble Strips

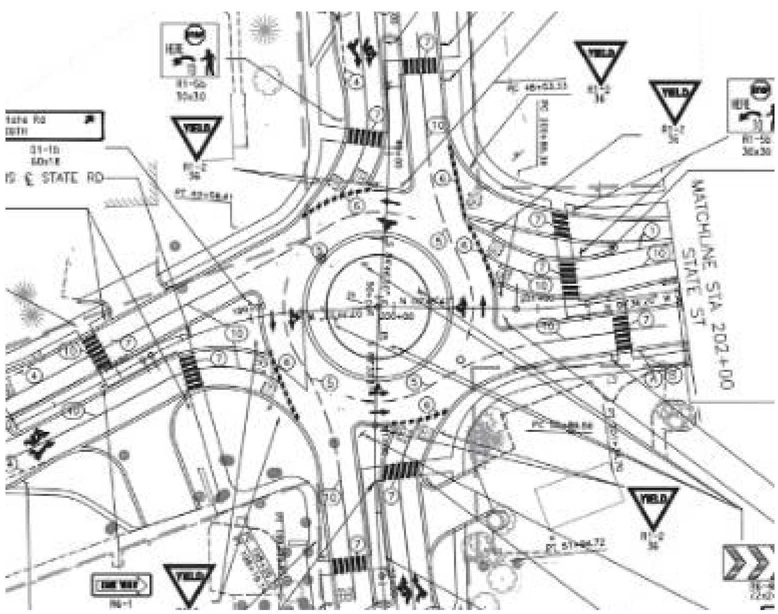


Figure 3-14: Two-Lane Roundabout with Milled Rumble Strips in Ann Arbor, MI

3.2.3.5 Cary, NC

The team collected data at a single-lane roundabout in Cary, NC in November 2014. The site at the intersection of Old Apex Road and West Chatham Street is a single-lane location with three approach legs. The team studied the west approach on Old Apex Road.

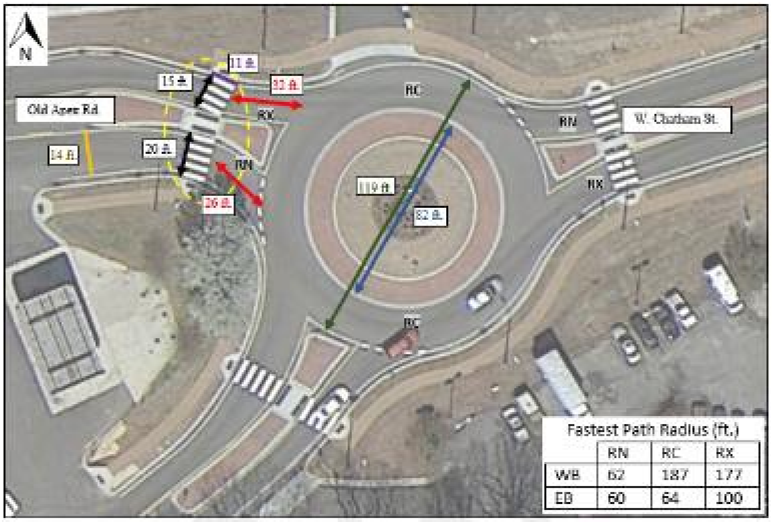


Figure 3-15: Roundabout Site at Old Apex Road and West Chatham Street in Cary, NC

3.3 Modeling Overview

The following list summarizes the critical modeling needs identified in this research. Most of these models are part of the crossing assessment methodology, with some focus on wayfinding.

1. Safety and Risk Prediction Models for All Three Facility Types
2. Yield Model for Single-Lane Roundabouts and Channelized Turn Lanes
3. Free-Flow Speed Prediction Model of Vehicle Speeds at Crosswalks
4. Wayfinding Assessment Tools
5. Crossing Alignment Assessment Tools
6. Gap Utilization Models for All Three Facility Types
7. Yield Utilization Models for All Three Facility Types

The models above are those that have been identified as key assessment steps and that have not been developed in prior research. Each model was developed in Phase II of this project based on empirical data at existing sites and new data collected in this project. Table 3-3 lists all models by facility types, including a count of existing and new study locations proposed for each modeling effort. The table also lists the data source from one or more studies of the Accessibility Audit protocol described above.

Modeling results are discussed in detail in Chapter 5 of this document and are incorporated into the guidebook deliverable.

Table 3-6: Modeling Needs and Site Selection

#	Model Type	Facility Type	# of Existing Sites	# of New Sites	Data Source
1a	Safety and Risk Prediction Model	CTL	3	12	Indicator Study
1b	Safety and Risk Prediction Model	Single RBT	3	2	Indicator Study
1c	Safety and Risk Prediction Model	Multi RBT	10	6	Indicator Study
2a	Yield Model	CTL	3	12	Yielding Study
2b	Yield Model	Single RBT	3	2	Yielding Study
3a	Free-Flow Speed Prediction Model	CTL	3	12	Free-Flow Speed Study
3b	Free-Flow Speed Prediction Model	Single RBT	3	2	Free-Flow Speed Study
3c	Free-Flow Speed Prediction Model	Multi RBT	10	6	Free-Flow Speed Study
4	Wayfinding Assessment	All	16	20	Wayfinding Study and Geometry Audit
5	Crossing Alignment Tool	All	16	20	Wayfinding Study and Geometry Audit
6a	Gap Utilization Model	CTL	3	12	Indicator Study
6b	Gap Utilization Model	Single RBT	3	2	Indicator Study
6c	Gap Utilization Model	Multi RBT	10	6	Indicator Study
7a	Yield Utilization Model	CTL	3	12	Indicator Study
7b	Yield Utilization Model	Single RBT	3	2	Indicator Study
7c	Yield Utilization Model	Multi RBT	10	6	Indicator Study

3.4 IRB Approval

The team requested and obtained approval for all studies necessary from the Institutional Review Board (IRB) of North Carolina State University and of the National Academy of Sciences. Both IRB boards approved the study protocols as described.

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4 FIELD STUDY RESULTS

This chapter presents a summary of the field studies for the eight roundabout and 12 channelized turn lane sites included this research. The first part of the chapter presents the actual field study results in the form of simple lists accompanied by photos. The second part of the chapter provides a narrative of observations for the various sites. Additional detailed results are provided in Appendix E.

4.1 Summary of Field Studies

This section presents a summary of the field study results, starting with the channelized turn lane sites, and followed by the roundabout sites. The results cover the results of the crossing indicator study with blind participants (producing measures of intervention rate and delay), yielding study (producing measure of yielding rate), and vehicle free-flow speed study (producing the average speed of vehicles at the crosswalk). Results for the wayfinding studies are discussed in Section 4.2 and Appendix A. Results of the site photo logs are presented in Appendix E. Additional field study details are provided in Appendix F.

4.1.1 Channelized Turn Lane Sites

A total of 12 channelized sites were studied in this research, with sites located in Tucson, AZ (4 sites), Boulder, CO (6 sites), Greenbelt, MD (1 site), and Cary, NC (1 site). The results are presented below in sequence.

4.1.1.1 Tucson, AZ

Four channelized turn lanes were studied in Tucson, AZ as listed below.

1. Wilmont Road at Speedway Boulevard – Northwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, stop sign at downstream merge point
    a. Intervention Rate: 2.2%
    b. Average Delay: 6.3 seconds
    c. Yielding Rate: 88.6%
    d. Average Speed (200’): G – 33 mph; R – 28 mph
    e. Average Speed (CW): n/a (stop sign)

Figure 4-1: Wilmont Road at Speedway Boulevard, NW Quadrant, Tucson, AZ

2. Sabino Canyon Road at Tanque Verde Road – Northeast quadrant of intersection, urban location, deceleration and acceleration lane, no additional treatments
    a. Intervention Rate: 0.0%
    b. Average Delay: 4.2 seconds
    c. Yielding Rate: 46.6%
    d. Average Speed (200'): G – 30 mph; R – 28 mph
    e. Average Speed (CW): G – 22 mph; R – 19 mph

Figure 4-2: Sabino Canyon Road at Tanque Verde Road, NE Quadrant, Tucson, AZ

3. Grant Road at Oracle Road – Northeast quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk
    a. Intervention Rate: 0.0%
    b. Average Delay: 3.0 seconds
    c. Yielding Rate: 67.9%
    d. Average Speed (200'): G – 31 mph; R – 30 mph
    e. Average Speed (CW): G – 21 mph; R – 19 mph

Figure 4-3: Grant Road at Oracle Road, NE Quadrant, Tucson, AZ

4. Grant Road at Oracle Road – Southwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk
    a. Intervention Rate: 6.7%
    b. Average Delay: 3.7 seconds
    c. Yielding Rate: 49.5%
    d. Average Speed (200'): G – 32 mph; R – 29 mph

e. Average Speed (CW): G – 20 mph; R – 17 mph

Figure 4-4: Grant Road at Oracle Road, SW Quadrant, Tucson, AZ

4.1.1.2 Boulder, CO

Six channelized turn lanes were studied in Boulder, CO as listed below.

1. 28th Street at Pearl Street – Northeast quadrant of intersection, urban location, deceleration lane, no acceleration lane, no additional treatments

    a. Intervention Rate: 8.5%
    b. Average Delay: 12.2 seconds
    c. Yielding Rate: 66.0%
    d. Average Speed (200’): G – 25 mph; R – 21 mph
    e. Average Speed (CW): G – 14 mph; R – 13 mph

Figure 4-5: 28th Street at Pearl Street, NE Quadrant, Boulder, CO

2. 28th Street at Pearl Street – Northwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk

    a. Intervention Rate: 1.7%
    b. Average Delay: 15.7 seconds
    c. Yielding Rate: 57.8%
    d. Average Speed (200’): G – 26 mph; R – 20 mph
    e. Average Speed (CW): G – 15 mph; R – 13 mph

Figure 4-6: 28th Street at Pearl Street, NW Quadrant, Boulder, CO

3. 28th Street at Canyon Boulevard – Southwest quadrant of intersection, urban location, deceleration lane, no acceleration lane, raised crosswalk
   a. Intervention Rate: 6.7%
   b. Average Delay: 23.9 seconds
   c. Yielding Rate: 40.3%
   d. Average Speed (200'): G – 29 mph; R – 27 mph
   e. Average Speed (CW): G – 15 mph; R – 14 mph

Figure 4-7: 28th Street at Canyon Boulevard, SW Quadrant, Boulder, CO

4. Foothills Parkway at Arapahoe Avenue – Southwest quadrant of intersection, suburban location, deceleration lane, acceleration lane, raised crosswalk
   a. Intervention Rate: 0.0%
   b. Average Delay: 14.6 seconds
   c. Yielding Rate: 32.4%
   d. Average Speed (200'): G – 33 mph; R – 35 mph
   e. Average Speed (CW): G – 21 mph; R – 22 mph

Figure 4-8: Foothills Parkway at Arapahoe Avenue, SW Quadrant, Boulder, CO

5. Foothills Parkway at Baseline Drive – Southwest quadrant of intersection, suburban location, deceleration lane, acceleration lane, sound strip treatment
    a. Intervention Rate: 0.0%
    b. Average Delay: 9.8 seconds
    c. Yielding Rate: 30.5%
    d. Average Speed (200'): G – 28 mph; R – 29 mph
    e. Average Speed (CW): G – 20 mph; R – 18 mph


Figure 4-9: Foothills Parkway at Baseline Drive, SW Quadrant, Boulder, CO

6. Foothills Parkway at Baseline Drive – Northeast quadrant of intersection, suburban location, deceleration lane, acceleration lane, raised crosswalk
    a. Intervention Rate: 0.0%
    b. Average Delay: 13.0 seconds
    c. Yielding Rate: 36.1%
    d. Average Speed (200'): G – 33 mph; R – 31 mph
    e. Average Speed (CW): G – 25 mph; R – 22 mph

Figure 4-10: Foothills Parkway at Baseline Drive, NE Quadrant, Boulder, CO

4.1.1.3 Greenbelt, MD and Cary, NC

Finally, one channelized turn lane each were studied in Greenbelt, MD and Cary, NC as listed below.

1. Kenilworth Avenue at East West Highway - Northwest quadrant of the intersection, deceleration lane, no acceleration lane, no other treatments installed
    a. Intervention Rate: 10.4%
    b. Average Delay: 20.1 seconds
    c. Yielding Rate: 23.2%
    d. Average Speed (200’): G – 28 mph; R – 29 mph
    e. Average Speed (CW): G – 17 mph; R – 15 mph

Figure 4-11: Kenilworth Avenue at East West Highway, NW Quadrant, Greenbelt, MD

2. Kildaire Farm Road at Tryon Road – Southwest quadrant of the intersection, deceleration lane, no acceleration lane, no other treatments installed
    a. Intervention Rate: 3.3%
    b. Average Delay: 16.0 seconds
    c. Yielding Rate: 46.8%
    d. Average Speed (200’): G – 38 mph; R – 35 mph
    e. Average Speed (CW): G – 15 mph; R – 13 mph

Figure 4-12: Kildaire Farm Road at Tryon Road, SW Quadrant, Cary, NC

4.1.2 Roundabout Sites

A total of 8 roundabout approaches were studied in this research, with each location featuring an entry and an exit leg for a total of 16 data points. The sites were located in Hilliard, OH (2 entry legs, 2 exit legs), Oakland County, MI (2 entry legs, 2 exit legs), Greenbelt, MD (1 entry leg, 1 exit leg), Ann Arbor, MI (2 entry legs, 2 exit legs) and Cary, NC (1 entry leg, 1 exit leg). The results are presented below in sequence with photos.

4.1.2.1 Hilliard, OH

1. Main Street at Cemetery Road – East and west approaches, two-lane entries and exits, west approach features a “standard” crosswalk location, east approach features an offset or “zig-zag” configuration, both approaches have in-road yield to pedestrian signs
   a. Intervention Rate:
      - East Entry: 1.7%
      - East Exit: 6.7%
      - West Entry: 1.9%
      - West Exit: 14.0%
   b. Average Delay:
      - East Entry: 21.7 seconds
      - East Exit: 17.4 seconds
      - West Entry: 14.8 seconds
      - West Exit: 17.9 seconds
   c. Yielding Rate:
      - East Entry: 58.9%
      - East Exit: 23.4%
      - West Entry: 63.6%
      - West Exit: 21.3%
   d. Average Speed (CW):
      - East Entry: 17 mph
      - East Exit: 26 mph
      - West Entry: 16 mph
      - West Exit: 21 mph

Figure 4-13: Main Street at Cemetery Road, East Approach, Hilliard, OH

4.1.2.2 Oakland County, MI

1. Maple Road at Farmington Road – East and south approaches, RRFB on all approaches, raised crosswalk on tested approaches only, three-lane east leg, two-lane north and south legs
    a. Intervention Rate:
        - East Entry: 0.0%
        - East Exit: 0.0%
        - South Entry: 0.0%
        - South Exit: 6.0%
    b. Average Delay:
        - East Entry: 9.4 seconds
        - East Exit: 10.9 seconds
        - South Entry: 9.3 seconds
        - South Exit: 8.2 seconds
    c. Yielding Rate:
        - East Entry: 90.8%
        - East Exit: 54.1%
        - South Entry: 65.2%
        - South Exit: 65.4%
    d. Average Speed (CW):
        - East Entry: 13 mph
        - East Exit: 15 mph
        - South Entry: 13 mph
        - South Exit: 15 mph

Figure 4-14: Maple Road at Farmington Road, East Approach Exit, Oakland County, MI

Figure 4-15: Maple Road at Farmington Road, South Approach Entry, Oakland County, MI

4.1.2.3 Greenbelt, MD

1. Greenbelt Metro Drive at Cherrywood Lane – West entry and west exit approaches, raised crosswalks, one-lane entry, two-lane exit
    a. Intervention Rate:
        - West Entry: 2.1%
        - West Exit: 4.0%
    b. Average Delay:
        - West Entry: 24.0 seconds
        - West Exit: 26.2 seconds
    c. Yielding Rate:
        - West Entry: 41.9%
        - West Exit: 13.7%
    d. Average Speed (CW):
        - West Entry: 17 mph
        - West Exit: 17 mph

Figure 4-16: Greenbelt Metro Drive at Cherrywood Lane, West Entry and Exit Approaches, Greenbelt, MD

4.1.2.4 Ann Arbor, MI

1. Ellsworth Road at State Road – West entry and west exit approaches, "zig-zag" crosswalk, rumble strips
    a. Intervention Rate:
        - West Entry: 0.0%
        - West Exit: 3.1%
    b. Average Delay:
        - West Entry: 7.9 seconds
        - West Exit: 9.9 seconds
    c. Yielding Rate:
        - West Entry: 78.3%
        - West Exit: 8.0%
    d. Average Speed (CW):
        - West Entry: 18 mph
        - West Exit: 27 mph

Figure 4-17: Ellsworth Road at State Road, West Entry and Exit Approaches, Ann Arbor, MI

2. Nixon Road at Huron Parkway – South entry and south exit approaches, single-lane roundabout, rumble strips
    a. Intervention Rate:
        - West Entry: 0.0%

- West Exit: 0.0%

b. Average Delay:
   - West Entry: 5.8 seconds
   - West Exit: 8.4 seconds

c. Yielding Rate:
   - West Entry: 79.4%
   - West Exit: 45.5%

d. Average Speed (CW):
   - West Entry: 15 mph
   - West Exit: 16 mph

Figure 4-18: Nixon Road at Huron Parkway, South Exit and Entry Approaches, Ann Arbor, MI

4.1.2.5 Cary, NC

1. Old Apex Road at West Chatham Street – West entry and west exit approaches, three-legged, single-lane roundabout

   a. Intervention Rate:
      - West Entry: 1.7%
      - West Exit: 3.3%

   b. Average Delay:
      - West Entry: 11.4 seconds
      - West Exit: 11.7 seconds

   c. Yielding Rate:
      - West Entry: 61.4%
      - West Exit: 32.2%

   d. Average Speed (CW):
      - West Entry: 18 mph
      - West Exit: 21 mph

Figure 4-19: Old Apex Road at West Chatham Street, West Entry and Exit Approaches, Cary, NC

4.2 Field Observations and Descriptive Data on Wayfinding

As discussed earlier, blind participants were asked to find the crosswalk and to cross at the roundabout and CTL sites after completing the indicator trials. The wayfinding trials were conducted at a subset of intersections for the indicator trials. Before the indicator trials, participants were given a general orientation to the roundabout or CTL, which focused on traffic movement characteristics. Details of the crosswalks or islands were not described or explored as part of the orientation. At most sites, the participant had walked up to the crosswalk numerous times during the indicator trials, so some participants were familiar with one approach. However, they had not approached from both directions and had only crossed to the island once or twice to get an idea of the width of the lane they were judging.

Each participant completed two approaches at each location, usually one from each of the two possible approach directions, with the crosswalk ahead on the right on one approach and on the left on the other approach. There were some locations where the sidewalk did not continue past the crosswalk, so both approaches were made from the same direction. The actions of the participants were observed and recorded, as detailed in Appendix A, and observations were recorded by researchers, who were certified orientation and mobility specialists (COMS), about the common problems observed and the features that seemed to affect wayfinding behavior. This observational information was generally supported the descriptive statistics reported in Appendix A.

4.2.1 Wayfinding Features – Summary of Observational Data

Summaries of the observations made by O&M specialists during the wayfinding trials are organized below by the types of errors observed during the data collection. The comments and impressions of blind participants were also noted in discussion with researchers after each set of wayfinding trials, and are summarized here and in Appendix A.

The description of the observations is organized by the wayfinding tasks of interest:

1) Determining the Crossing Location, including detecting the street,

2) Aligning to Cross and Establishing a Correct Heading, and

3) Maintaining Correct Heading While Crossing (e.g., staying within the crosswalk).

An additional section discusses features of intersections that may affect wayfinding for persons who are blind, such as the pushbutton location of pedestrian signals. Tasks 1-3 were completed from the curb to the island, while only the first and second tasks were completed after participants had crossed to the island. Some observations relate mainly to the island wayfinding features

Note that islands that are delineated only by pavement markings are not recognized at all by pedestrians who are blind.

4.2.2 Determining the Crossing Location

Typical strategies at signalized and stop-controlled intersections for locating a curb ramp or crossing location leading to a crosswalk include continuing to the curb in the direction of travel while approaching the intersection, and identifying traffic stopped at the stop line on the perpendicular street as a cue to the crosswalk location. At roundabouts this strategy can prove difficult to implement. Because of the curving nature of the sidewalk, individuals may find it difficult to recognize the desired crossing point. To locate the crosswalk at a roundabout or CTL, participants often had to follow (tactually, using their cane) a landscape edge to their side, or the curb itself, using various cues to locate the crossing location. These cues may include changes in the landscaping, curb ramps, or the presence of detectable warning surfaces. It appeared that most participants were unaware of the need to walk on the side of the sidewalk closest to the street to find the crossing location. Also, because most of the cues to the location of the crossing point do not extend for the full width of the sidewalk, they will not likely be detected by pedestrians who are blind, if they are walking on the sidewalk and away from the street. When prompted that they had passed the crosswalk, many participants began to follow or "trail" the edge of the landscaping near the curb, or follow the curb itself.

The second aspect of locating the crosswalk location is detecting the street and stopping before stepping into the street. Recognizing the curb or the slope of the curb ramp, the detectable warning surface, and the gutter along the edge of the street, are typically the key cues used to recognize the edge of the street, either at the curb edge or when crossing from the islands.

Whether considering the data in Appendix A, Figures 14-1 through Figure 14-6, or the data for each intersection location as shown in Tables 14-4 through Table 14-7, it is clear that determining the crossing location can be a significant problem for many blind pedestrians. For example, Table 14-4 and Table 14-6 show that large percentages of participants missed the crosswalk at most of the roundabout sites. This was true both for the crosswalk leading to an island and for crosswalks leading from the island to the curb. However, there were a few exceptions to this general finding at some roundabout locations. Also, like these exceptions at roundabouts, Table 14-5 indicates that, for the CTL sites, most of the crossing locations *on trials to the island* were successfully located by the participants. It is unclear what factors accounts for the wide variations across sites and individuals. It appears from the research conducted in this project that the design of an accessible roundabout or CTL for persons who are blind requires additional study in order to better understand why determining the crossing location is a substantial challenge when traveling without vision, and to determine what travel strategies and environmental modifications aid individuals in successful completion of this key wayfinding task.

4.2.2.1 Features that appeared to aid in determining the crossing location (locating the crosswalk)

a) Grass or other landscape strip between sidewalk and curb

When there was a landscape strip between the sidewalk and curb, blind pedestrians usually did not walk on it, and instead stayed on the sidewalk while looking to the side with their cane for the crosswalk. Participants reported that they were more comfortable when looking for the crosswalk when they were separated by landscaping from traffic moving in the roadway. Not all participants used the strategy of following, or trailing the landscape strip on their side closest to the roadway with their cane when looking for the opening to the crosswalk at first. Most participants adopted that strategy (if there was a landscape strip) after they were told that they had passed the crosswalk.

Figure 4-20: Grass between sidewalk and curb along edge of circulatory roadway between the crosswalks

> *This figure shows a photo of a roundabout with an approximately 4-foot-wide grass strip between the sidewalk and the roadway that follows the curvature of the road between the crosswalks at a roundabout.*

b) Grass or gravel outside the crosswalk area, particularly on islands.

If there was grass or a gravel type surface that felt different under foot than pavement, blind participants usually did not continue walking on it, but looked with their cane of foot for a sidewalk-type surface on which to travel. Less disorientation and confusion was noted on islands with landscaped or graveled areas.

Figure 4-21: Gravel landscape strip provides detectable edge of sidewalk for person who is blind and separation between the sidewalk and CTL travel lane

> *This figure shows a photo of an approximately 3-foot-wide gravel strip between the sidewalk and the roadway that follows the curvature of the road to the crosswalk at a CTL.*

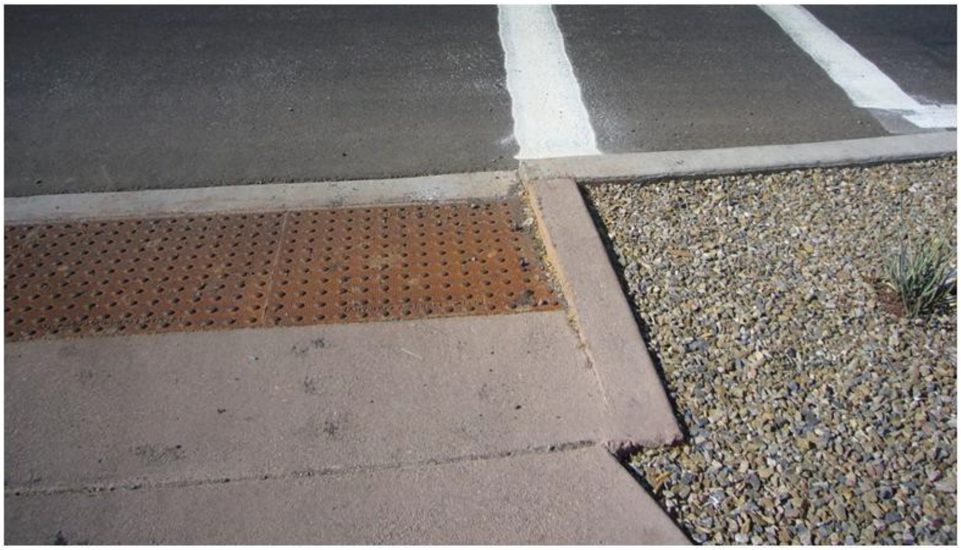

Figure 4-22: Gravel or grass outside the crosswalk and walkway area

Photo of a curb ramp leading to a crosswalk, with detectable warning surface on the ramp, returned curb on the ramp and gravel landscaping outside the sidewalk area.

4.2.2.2 Features that didn't seem to provide adequate information to pedestrians who were blind in locating the crosswalk

a) Paved or hardscape surfaces

For pedestrians who were blind, paved or hardscape surfaces, even with those with had a relatively rough texture, were not observed to provide a reliable cue that the area was not the sidewalk area. At one roundabout location, cobblestone pavers were used for separation between the roadway and sidewalk, as shown in the photo below, but blind pedestrians walked on that surface, sometimes lining up to cross the roundabout at the assumed "corner" leading across the circulatory roadway, or alongside the circulatory roadway, but not at the crosswalk.

Sidewalks at back of curb required blind pedestrians to follow the curb line with their cane, walking dangerously (and uncomfortably) close to traffic along the curving sidewalk, searching for the slope of a curb ramp, detectable warnings or other indication of the crosswalk.

On islands, if the area outside the cut-through walkway was paved, some participants stepped up onto the island and were confused when they contacted the cut-through area, thinking the cut-through was the street rather than a pedestrian walkway.

Figure 4-23: Pavers, with fairly rough texture (cobblestone)

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

Figure 4-24: Sidewalk at back of curb with no landscape separation

Photo of a 5-foot-wide sidewalk that is right behind the curb, with a guard rail on the back side of the sidewalk. Crosswalk is visible ahead and a bus is in the lane close to the sidewalk, leaning toward the sidewalk. Blind pedestrians have to follow the curb line with their cane to find the detectable warning surface and curb ramp in order to locate the crosswalk. Does not provide separation required by proposed PROWAG

Figure 4-25: Paved colored surfaces do not provide adequate cues

Photo shows a portion of an island where reddish color was added to the island pavement outside the white concrete pedestrian pathway between the crosswalks. Blind pedestrians did not walk within the concrete pathway through island and did not consistently locate the proper clossing location for the crossing from the island.

At locations with parallel curb ramps, it appeared that participants were unfamiliar with this type of ramp design. Parallel curb ramps are most often used where there is limited right-of-way and the sidewalk is at back of curb. The entire sidewalk slopes down to a level landing, or turning space, where the crosswalk is located. Some blind participants stopped on the slope, parallel to the crossing, thinking that they had reached an edge of the street when they reached the level landing. This slope and the need to turn 90 degrees to cross were confusing to them. Some blind participants mistook the curb at the back of the ramp for the edge of the street and attempted to cross from behind or on top of the curb. Alignment cues are limited and the landing is often level with the street. Parallel curb ramps are described and shown in Figure 4-26.

Figure 4-26: Parallel ramp, showing curb at back of ramp

> *Photo shows a parallel curb ramp at a roundabout crossing. There is no landscaping or barrier between the sidewalk and the curb. The entire 5-foot wide sidewalk slopes down to a level landing at the crosswalk location. The detectable warning surface is installed along the curb line for the width of the level area. There is a curb at the back of the sidewalk behind the landing to keep dirt and gravel from washing onto the landing area.*

4.2.3 Detecting the Street

Another aspect of locating the crosswalk is recognizing the street edge. At most locations, detectable warning surfaces were installed to indicate the edge of the street at curb ramps. The detectable warning surface must extend the full width of area that is level with the street to provide an adequate warning.

At the roundabout and CTL locations where detectable warnings were not installed or did not extend the full width of the level area, some research participants continued into the street without recognizing that they had walked into the street. This occurred at locations where there was no detectable warning surface and where the detectable warning did not extend the full width of the cut-through area on the islands.

Note that there is a considerable body of research regarding the detectability of underfoot surfaces by persons who are blind, either using their foot or the long cane for detection. Surfaces used in some locations, such as the scored concrete shown in Figure 4-27, are not among the surfaces that have been shown in research to be reliably detectable.

Figure 4-27: CTL with raised crosswalk and no detectable warning surfaces. Scored concrete is not detectable.

Photo shows a raised crosswalk leading to an island. There are no detectable warning surfaces to indicate the edge of the street, either on the curb or the island. The concrete sidewalk is scored with approximately 12-inch squares, but as noted in text, that scoring is not detectable under foot or with a cane. Crosswalk markings in this photo are also very faded.

At locations with raised crosswalks where changes in elevation between street and curb ramp are not present, the detectable warning surface is the only clue to the location of the edge of the street. If detectable warnings were not installed, participants were likely to walk into the vehicular lanes (Figure 4-27). However, even where detectable warnings were installed, participants walked into the street if they approached from an angle that allowed them to continue without stepping off the curb or actually crossing the detectable warning surface (Figure 4-28).

Figure 4-28: View of raised crosswalk where some participants did not find detectable warnings

Photo of a raised crosswalk at a CTL where detectable warnings were installed, but there was a level area on each side of the crosswalk where a pedestrian approaching at an angle could walk in to the street without contacting the detectable warning surface. A participant walking in the direction shown by the arrow could walk into the street without contacting the detectable warning surface because the sidewalk was level with the street where the arrow is pointing

Detecting the street is also important at both edges of both triangular islands at CTLs and splitter islands at roundabouts. Islands with cut-through walkways and no detectable warnings at each edge of the island were undetected by blind participants at both roundabouts and CTLs during the wayfinding studies. Where the island was not detected, participants usually failed to stop before entering other lanes of the roadway. If the island is intended as a refuge, and if pedestrians are expected to stop and consider the traffic on the other portion of the roadway before continuing, detectable warning surfaces must be installed for the entire width of the cut-through area and should extend at least 24" in the direction of travel at the edge of the island on each side of the island. At locations where the islands are not close to the crosswalk edges, as shown in Figure 4-29, blind pedestrians did not recognize that there was a potential refuge area, while sighted pedestrians made two-stage crossings, pausing at the islands to wait for gaps in traffic.

Figure 4-29: Roundabout without detectable surfaces or refuge in splitter islands.

> *Photo of a crosswalk where the raised island portions do not extend to the edges of the crosswalk and there is also no detectable warning surface at the island location to delineate the edges of the island to blind pedestrians. Islands were not detectable. This resulted in pedestrians needing to make a full crossing rather than being able to make a 2 stage crossing*

Comments from participants also indicated that they felt more confident detecting the street where there was a slope difference as well as the detectable warning surface. They generally preferred islands that had a curb ramp and raised island rather than where the walkway was cut through at the level of the roadway. For wayfinding through the island with curb ramps, participants performed best with a paved walkway area and grass or gravel surfaces outside the walkway area.

4.2.4 Aligning to Cross

It is important that individuals align themselves when preparing to cross a street so that they are facing more or less toward the curb ramp on the opposite side of the street. If they are significantly misaligned, they may walk toward or away from the intersection, and sometimes may become disoriented. Walking more or less directly across may be challenging for travelers who rely only on nonvisual cues. When aligning to cross, blind pedestrians used a combination of cues, including underfoot surfaces and traffic movement. The direction of vehicular traffic across the crosswalk, the alignment of the approach sidewalk, the detectable warning surface, the slope of the ramp, and the gutter/edge of street are all cues that may be used by individuals who are blind. While none of these cues are consistently oriented parallel or perpendicular to the direction of travel on the crosswalk (regardless of the type of intersection to be negotiated), and none of them are sufficient to enable accurate alignment (even if they are aligned with the crosswalk), they all contribute to alignment decisions.

At locations where all cues named above provided the same information, individuals were more likely to begin their crossing aligned within the crosswalk. Where there were mixed messages regarding the direction of travel, various techniques and cues were used across participants and across times of day. If traffic was heavy, the direction of vehicular traffic across the crosswalk seemed to influence decisions more than at times when traffic was light.

Despite some limitations of the wayfinding component of this project in terms of site selection and sample size (discussed elsewhere in this report), the descriptive data of Appendix A suggest that aligning to cross is a major problem at most roundabouts and CTL's. Unlike the previously discussed data for determining the crossing location, there were very few sites or conditions where participants consistently aligned successfully, and the alignment failure rates tended to be very large. While a few design features appeared to help in aligning to cross, as discussed below, the overwhelming weight of the observational and descriptive evidence suggests that blind pedestrians align poorly at roundabouts and CTL's. For example, omnibus Figure 14-1 in Appendix A shows that, overall, initial alignment error rates averaged 34% at roundabouts and 43% at CTL's. For the micro level of individual sites, Table 14-4 shows very high rates of initial alignment error at all but one of the CTL's. This pattern of consistent and high levels of error is evident across all of the relevant Appendix A tables and figures. While our results invite stronger scrutiny of the problem with more focused experiments, they unfortunately do not provide much evidence that the particular crosswalk designs evaluated in this project promote alignment success. It may be the case that additional design features, perhaps similar to the prototype features tested in other work by our team (described elsewhere in this report), will ultimately prove necessary to enable successful initial alignment.

4.2.4.1 Features that appeared to aid in aligning to cross

More accurate alignment decisions appeared to be made at locations where the approach to the crosswalk was aligned with the crosswalk, and where there were also returned curbs aligned with the direction of travel on the crosswalk. In addition, our observations the blind participants' stepping movements in seeking an alignment direction suggested they sometimes used the gutter of the street, detectable warning surface, and the slope of the ramp for alignment. Although individuals stated that they did not line up with the ramps, and research indicates that people who are blind do not accurately line up perpendicularly to ramp slope, many did appear to the observing O&M specialists to be adjusting their alignment direction relative to the combination of the ramp slope and the gutter orientation.

In most cases, the placement of the crosswalk can make a difference in the alignment of these features. For example, the base of curb ramps must be perpendicular to the gutter to avoid tipping by wheelchair users, so the location and angle of the ramp can be affected by the location on the curve of the roundabout or CTL roadway. Aligning all these features may require moving the crosswalk to a different point.

Figure 4-30: Approach direction, landscaping, returned curbs, detectable warning surface and crosswalk are all aligned, providing potential alignment cues for blind pedestrians

Photo shows a roundabout crosswalk where the approach, the edges of the landscaping, the detectable warning surfaces, and the gutter are generally aligned with the crosswalk direction.

4.2.4.2 Features that seemed to provide inadequate or confusing information to pedestrians who were blind in aligning to cross

When the various features mentioned above (the landscaping or edge of the sidewalk, the curb ramp slope, detectable warning surface, and edge of the street/gutter) were not aligned with the crosswalk direction, participants appeared more likely to be misaligned. In the examples shown in Figure 4-31 and Figure 4-32, the crosswalk angled slightly to the right, while the other cues were aligned toward the left, which appeared to cause confusion. This geometric situation is seen fairly commonly when a crosswalk is close to the roundabout's circulatory roadway, since the curb ramp must intersect the gutter at right angles to be accessible to wheelchair users and avoid a tipping hazard. This was also noted at several CTL crosswalks.

Figure 4-31: Landscaping, curb ramp slope, detectable warning surface and gutter are not aligned with direction of travel on the crosswalk. This appeared to lead to alignment errors by blind pedestrians

Photo of a curb ramp, crosswalk and island. The ramp, detectable warning surface and gutter all are aligned to the left of the crosswalk direction. The splitter island, which has a wider cut-through area than the crosswalk width, has detectable warning surfaces covering only a portion of the opening in the island.

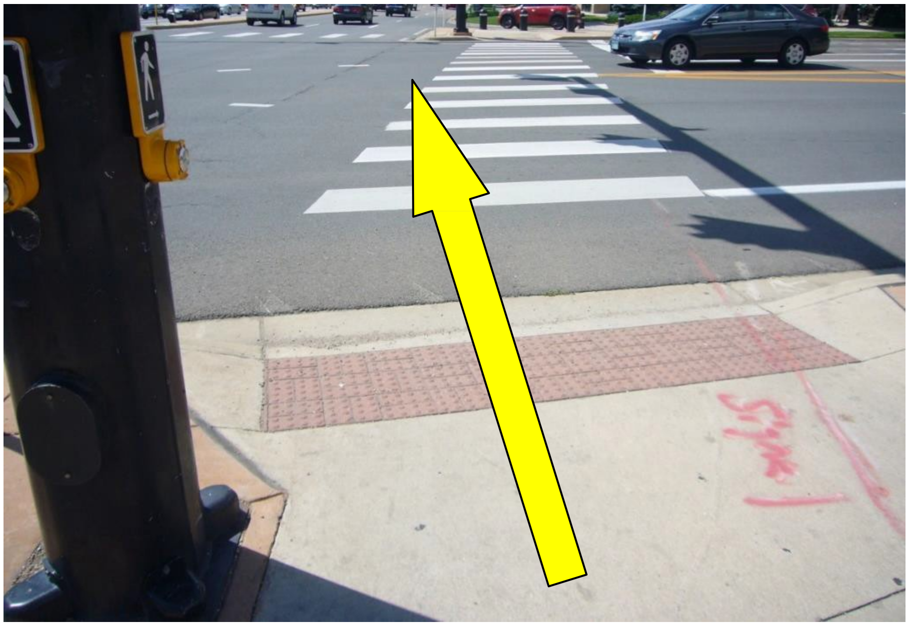

Figure 4-32: Ramp slope, detectable warning surface and gutter are all aligned to left of crosswalk direction

Photo of a crosswalk from a CTL island across the main signalized lanes of traffic. The curb ramp, detectable warning and gutter are all aligned to the left of the crosswalk direction. Blind participants appeared to align with these features into the traffic lanes, as shown by arrow. Traffic cues were also confusing at this slightly skewed intersection

At one CTL location, where participants were observed to be aligning themselves with the slope of the ramp and the line of the gutter, participants routinely missed the small island as they crossed. Instead, they inadvertently entered the main intersection outside of any marked crosswalks. This situation is shown in Figure 4-33.

Figure 4-33: At this location, some blind participants appeared to align themselves with the slope of the curb ramp and the line of the gutter, which led them to completely miss contacting the island.

Photo of a wide sidewalk approaching a crosswalk and a relatively small island at a CTL. The crosswalk is generally aligned with the sidewalk approach direction, however slope of the ramp and the gutter or grade break is at an angle left of the crosswalk direction.

Another feature of several locations was a cut-through area on the island that was narrower than the crosswalk, curb ramp, and landscaped area at the approach end of crosswalk. This situation can be problematic for large groups of sighted pedestrians, who must channelize themselves upon reaching the island. The issue for blind participants was largely one of confusion about their location as they contacted the island, but this was sometimes mitigated by island characteristics. For example, at the location shown in Figure 4-34 where there was a narrow cut-through area, with grass on other parts of the island, participants searched for the cut-through area and found it. At similar locations where there was a narrow cut-through area and a paved island, blind participants commonly stepped up onto the island and were confused and disoriented when they contacted the cut-through area, thinking that it was the street.

Figure 4-34: Cut-through is narrower than the crosswalk

> *Photo of crosswalk at CTL. Crosswalk is approximately 10-feet-wide and cut-through area of the grassy island at the end of the crosswalk is approximately 5 feet.*

4.2.5 Maintaining Correct Heading While Crossing and Staying Within the Crosswalk

At traditional, rectilinear intersections, blind pedestrians who are initially misaligned may, as a result of the misalignment, begin their crossing in the wrong direction. And even those blind pedestrians who are initially well aligned may veer from their intended heading as they walk and may therefore leave the crosswalk while crossing. Importantly, at traditional intersections, this initial heading error is typically detected and corrected on the basis of acoustic information about the trajectory of traffic moving parallel to the crosswalk. Experienced blind pedestrians can hear whether they are walking toward, away from, or parallel to the traffic moving next to them. If they hear that they are walking toward or away from this traffic, they then adjust their trajectory to be parallel to the traffic trajectory and thereby complete their crossing at the appropriate ending location.

However, at most roundabouts and CTL crossing locations, this “parallel traffic” is not present. Without such traffic, blind pedestrians have few, if any, environmental cues to help maintain a correct initial heading or to make corrections to an incorrect initial heading. Short crossings allow less opportunity to veer from the initial heading; however, so shorter crossing distances (i.e. narrow lanes) may be an advantage.

The research team expected raised crosswalks to assist blind participants to stay within the crosswalk, based on the assumption that any heading error would be corrected when participants detected cross slope on either side of the crosswalk when they contacted it with their cane or feet. However, the team did not observe raised crosswalks to be as helpful as expected. We speculate that many of the blind participants did not understand the design of the raised crosswalk well enough to recognize the cross slope as a cue that they were veering out of the crosswalk. With wide raised crosswalks and short crossing distances, there also were very few instances of veering outside the crosswalk.

It is important to note that well-marked crosswalks can provide important information to assist pedestrians with low vision stay within the crosswalk. However, participants in this research were all individuals without usable vision, so no data was gathered on the effect of crosswalk markings.

The Appendix A data for maintaining correct heading and staying within the crosswalk (which results in reaching the correct crossing ending location) were consistent with our observations, with all but the two roundabout sites in Ann Arbor, Michigan and one site in Cary, North Carolina showing high rates of failure to arrive at the crossing ending location. For example, Figure 14-1 shows that, overall, crossing ending location error averaged 18% at roundabouts and 38% at CTL's. At the level of individual sites, Table 14-4 and Table 14-5 show that with the exception of the three roundabout sites just mentioned, there were typically high rates of crossing ending location error at roundabouts. For the CTL sites, the lowest percentage failure for crossing ending location was 17% (at two Tucson, Arizona sites) and the highest was 70% (at one Boulder, Colorado site and one Tucson site).

While the need for rigorous follow-up to the descriptive wayfinding components of this project has been emphasized throughout this report, the widespread and high rates of our blind participants' challenges in arriving at the appropriate ending location are unacceptable but somewhat expected. These are complex travel situations, and our participants typically had little or no experience with CTLs and roundabouts. However, widely accepted definitions of "accessibility" include access to intersections and other aspects of the public right-of-way *that individuals are not familiar with*, either at a general or intersection specific level. The challenges and associated task error rates we observed are unacceptable because no reasonable definition of "accessible" would include the task failure rates observed in our descriptive data, as preliminary as it is. But these data are also somewhat expected given that, with the exception of the raised crosswalks, there were few design features at the roundabouts and CTL's that might be expected to enhance the detection and correction of heading error. As for the previously discussed problem of alignment error, it may be the case that additional design features, perhaps similar to prototype guidestrip features tested in other work by our team (described in Section 2.3 of this report), will ultimately prove necessary.

The three roundabout sites where participants always succeeded in reaching the crossing ending location were the Nixon & Huron site in Ann Arbor (S entry and S exit – see Photo Log, Figures 12-155 through 12-157, and Figures 12-159 & 12-160), the Ellsworth & State site in Ann Arbor (W exit, Photo Log, Figures 12-149 through 12-151), and the Old Apex and Chantam site in Cary (W entry, Photo Log Figures 12-209 & 12-210). These crossings have several commonalities. First, the crosswalks are very wide (relative to the direction of pedestrian travel, "long" in the direction of vehicle travel), with most being nearly as wide as they are long. Second, these sites' potential alignment cues (curb/gutter, curb ramp, and returned curbs) were aligned or only slightly misaligned with the crosswalk. Third, three of the four crossings are single-lane, resulting in a short crossing (relative to the direction of pedestrian travel). We hypothesize that at these locations, the participants were initially reasonably well aligned, and that the wide crosswalks combined with the short crossing distances meant that a substantial amount of misalignment or veering error could be tolerated before the participants would have left the crosswalk before completing crossings. Appendix A includes specific data about these sites.

4.2.6 Other Features – Pushbuttons, Particularly on Islands

Pushbuttons for pedestrian signals, accessible pedestrian signals, RRFBs, or other devices must be located close to the crosswalk they control in order to be useful to pedestrians who are blind. Despite a locator tone on the accessible pedestrian signal shown in Figure 4-35, participants in the wayfinding study did not find the pushbutton for the crossing because it was located too far back from the street. If they searched for it, they turned around before they found it.

Blind participants also had a problem with using the correct pushbutton for their crossing. Most of the pushbuttons at locations where data was collected were not audible/accessible. Participants commonly pushed the wrong pushbutton on the island.

Figure 4-35: The APS pedestrian pushbutton on this island was not found by blind participants.

> *Photo taken from the center of a CTL island looking across a wide street with a marked crosswalk. In the foreground is a pole with an APS pushbutton on it, located in the grass about 2 feet to the right of the paved cut-through walkway leading to the crosswalk. The pole and pushbutton are approximately 15 feet from the edge of the street pictured, and the pushbutton locator tone was not audible more than 5 feet from the pushbutton.*

4.2.7 Summary

The primary features that appeared to enhance wayfinding at both roundabouts and CTLs included:

- Grass or other landscape strip between sidewalk and curb;
- Grass or gravel outside the crosswalk area, particularly on islands;
- Having all wayfinding cues for alignment (vehicular traffic across the crosswalk, approach direction, landscaping or edge of the sidewalk, the curb ramp slope, detectable warning surface, and edge of the street/gutter) provide the same information;
- Short crossings;
- Detectable warnings to indicate the edge of the street and islands; and
- Audible information devices or audible pedestrian signals that were located close to the crosswalk they control and properly oriented.

These features may need to be considered in designing roundabouts and CTLs. Location of crosswalks and landscaping near the crosswalk and on the island can be key features that influence accessibility of these types of intersections. Training of blind pedestrians cannot improve wayfinding in an environment without usable cues.

Among the limitations of this early wayfinding study are differences in where participants began their trials (varied from 10 feet to over 100 feet from the crosswalk), differences in trial sample sizes across study locations, and differences in the wayfinding abilities of the participants (especially differences in ability between subjects who are typically dependent on dog guides for navigation and those who are not) that may act as confounds. Despite the recognized limitations of the wayfinding component of this project, the team believes that, taken together, the observational and descriptive findings suggest that wayfinding challenges pose serious problems to the accessibility of roundabouts and CTL's. We urge policy makers and designers to support further research to better document, understand, and mitigate these challenges.

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5 MODELING AND APPLICATIONS

This chapter presents an overview of nine of the methodological steps from the crossing assessment methodology shown in Chapter 7 of the NCHRP 03-78b guidebook. A list of these models is presented in Table 5-1, followed by more detailed discussion. The table illustrates in which step in the Guidebook Chapter 7 method the models are used, as well as the form of the model.

Table 5-1: Overview of Predictive Models

Model Type and Name	Methodology Step	Model Form	Details in Section
Free-Flow Speed Model	2	Traffic Flow Theory	5.1
Crossing Sight Distance	3	Traffic Flow Theory	5.2
Gap Opportunity Model	5	Traffic Flow Theory	5.3
Yield Opportunity Model	5	Regression	5.4
Gap Utilization Model	6	Table	5.5
Yield Utilization Model	6	Table	5.6
Audible Environment	7	Expert Judgment	5.7
Delay Model	8	Regression	5.8
Risk Performance Model	10	Regression	5.9

The results of this research are based on field data collection in several states across the country, but performance measures can vary significantly based on the local context of a specific site. This research recognizes the significance of different driver behaviors in different states, and it has attempted to identify and quantify the factors that are related to local context of the study locations. These include enforcement level, land use, and general level of driver courtesy in a particular area. However, caution should be taken when generalizing the models to other geographic regions or even specific municipalities that can have very unique driver and pedestrian cultures. It is highly recommended that as many parameters as possible are locally calibrated, and that the accessibility performance is verified through local and regional accessibility observations.

5.1 Free-Flow Speed Model

The first model is used to predict the vehicular free-flow speed in the vicinity of a crosswalk at roundabouts or CTLs. The model is a function of the geometric design of the roundabout or CTL, with the controlling variable being the *fastest path radius* at the crosswalk. High vehicular speed has been linked to a low probability of yielding through research, and so the estimate of free-flow speed is important to estimate for example a base yielding probability at the crosswalk in free-flow or non-congested conditions.

The model used to predict the speed of the crosswalk is the theoretical Fastest Path Speed model described in NCHRP Report 672 for roundabouts. This model in turn is adapted from speed-radius relationships found in the AASHTO Green Book. The free-flow speed model uses the following equations to show the speed-radius relationship for curves for both +0.02 super elevation:

$$V = 3.4415\ R^{0.3861}, \qquad e = +\ 0.02$$

The equation predicts the 85th percentile free-flow speed expected at the crosswalk as a function of *fastest path radius* (in ft.) that is believed to control the speed at the crosswalk. For roundabout entries, this speed is generally equal to the R1 term as shown in Figure 5-1. For roundabout exits, the radius of the corresponding movement (left, through, or right) is used, along with an acceleration constraint.

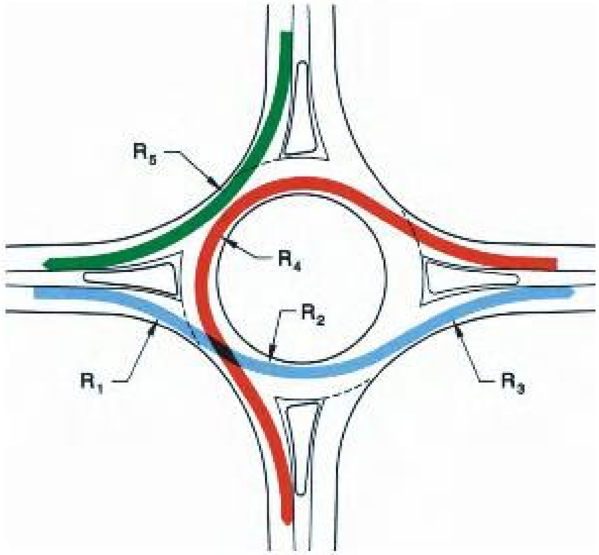

Figure 5-1: Roundabout Vehicle Path Radii (Source: NCHRP Report 672)

At a roundabout entry, this speed is principally a function of the R_1 radius shown in Figure 5-1. For exiting vehicles, the analyst can estimate an equivalent composite radius from terms R_2, R_4, and R_5 depending on whether the conflicting movement is a right-turning vehicle from the immediate upstream entry, or a through or left-turning vehicle from another entry. Since vehicles have an opportunity to accelerate leaving the roundabout, their actual speeds at the crosswalk are expected to be higher than those predicted by the respective controlling radii. As such, the speed is estimated at the fastest path radii, adjusted by acceleration of vehicles as described in NCHRP Report 672.

For CTLs, the equivalent of the R_1 radius is used to estimate the speed. The equivalent radius computations are summarized in Table 5-2.

Table 5-2: Equivalent Composite Radius for Speed Estimation

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

The model was compared to free- flow speed data for roundabout entries, roundabout exits, and channelized turn lanes. In particular, the model results were compared to the 85th percentile free-flow speeds at the crosswalk derived from a sample of at least 30 free-flowing vehicle speeds measured with a radar device. Figure 5-2 shows the fastest path equation above as a function of radius, with field-measured validation data for roundabouts and channelized turn lanes. Sites with raised crosswalks were excluded from the graph since speeds at those sites is not a function of radius alone.

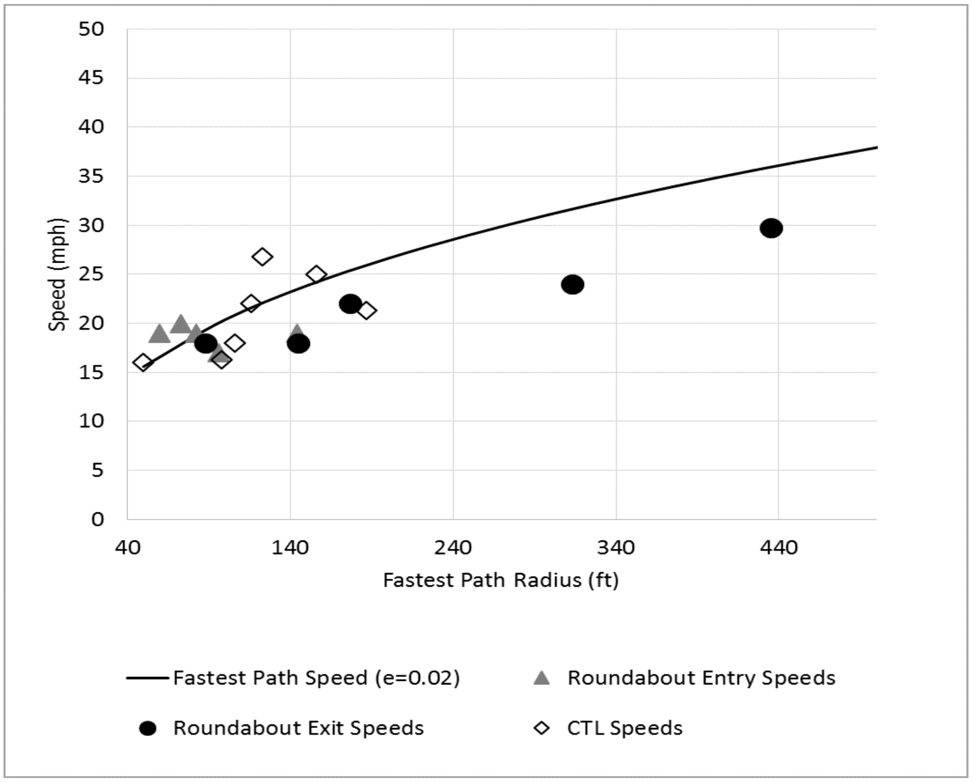

Figure 5-2: Free-Flow Speed Model Validation with Field Data

> *The figure shows a data plot with fastest path radius (in feet) on the x-axis and vehicle speed (in mi/h) on the y-axis. Four data series are plotted. The first series plots the fastest path radius and speed relationships for superelevation of +0.02 as a solid line. The remaining three data series show field measured data for roundabout entries (gray filled triangles), roundabout exits (black filled circles), and channelized turn lanes (black non-filled diamonds).*

The graph shows that the free-flow speed data collected from most sites, excluding the ones with raised crosswalks, can reasonably be approximated by the fastest path speed model. The proposed free-flow speed model therefore represents a reasonable approximation of the expected free-flow speeds at the crosswalks for sites without available speed data.

5.2 Crossing Sight Distance

In the AASHTO publication, *A Policy on the Geometric Design of Highways and Streets,* also known as the "Green Book," many design principles are based on the concept of sight distance calculations. Specifically, AASHTO distinguishes three types of sight distance: (1) stopping sight distance, (2) intersection sight distance, and (3) decision sight distance. These sight distances are used to guide the design of features such as minimum radii for horizontal and vertical curves, or to limit landscaping and sight obstructions at intersections and serve to reduce impedances to the driver's line of sight. The resulting design principles are also reflected in roundabout design guidelines (Rodegerdts et al., 2010), and apply equally to CTLs. To assure adequate design for vehicular movements, sight distance needs to be provided, and more specific guidance is available in aforementioned references.

In this section, c*rossing sight distance* is introduced as the distance required by pedestrians to recognize the presence of conflicting vehicular traffic and determine crossing opportunities at intersections and roundabouts. The distance is established through sight triangles that allow a pedestrian to evaluate potential conflicts with approaching vehicles. Similarly, the resulting sight triangles also assure that the driver has a clear view of a pedestrian waiting to cross or approaching the crosswalk. For pedestrians who are blind, the crossing sight distance applies in that any visual obstructions are also expected to impact the audible environment at the crosswalk and the ability to hear approaching vehicles without sound obstructions or deflections.

Although sight triangles are traditionally bound by linear vehicle paths, the roadway geometry of roundabouts and CTLs is non-linear. Therefore, sight distances are derived along the curvature of conflicting vehicular travel paths using the estimated vehicle speed and crossable gap times. This provides the distance for vehicles to travel along a path toward the crosswalk at their current speed in the amount of time needed for a pedestrian to cross the road safely. In other words, adequate crossing sight distance assures that a pedestrian can identify vehicles far enough away to provide sufficient time to cross the road. Adequate crossing sight distance also assures that drivers can see the pedestrian as he or she steps off the curb and into the roadway with sufficient time to react.

The methodology developed to determine crossing sight distance adequacy at a roundabout or CTL has been adapted from the sight distance performance check for *vehicles* at roundabouts from *NCHRP Report 672: Roundabouts: An Informational Guide – Second Edition* (Rodegerdts et al., 2010), calculations and definitions from the AASHTO "Green Book" (AASHTO, 2011), and the pedestrian mode methodology in Chapter 19 of the 2010 Highway Capacity Manual (TRB, 2010).

5.2.1 Assumptions and Inputs

The estimation of crossing sight distance requires several input variables and assumptions to execute the calculations. First, the calculation requires the estimation of a prevailing vehicle speed. This speed is estimated from site geometry (design radii), as well as speed prediction equations described in the previous section. Second, the calculation requires the estimation of a crossable gap time, which is a function of crossing distance, pedestrian walking speed, and any decision latency. A methodology for performing the crossable gap time estimation adapted from Highway Capacity Manual methods is shown below. Finally, the calculation requires some assumption of pedestrian and vehicle heights. In this chapter, an assumed height of 4 feet for pedestrians' eyes is used, as well as an assumed object height of 2.5 feet, consistent with AASHTO recommendations (AASHTO, 2011).

5.2.2 Crossing Sight Distance at Roundabouts

In general, there are two scenarios for pedestrians crossing approaches at roundabouts: (1) the pedestrian begins by crossing the entry lane(s) and ends by clearing the exit lane(s), and (2) the pedestrian begins by crossing the exit lane(s) and ends by clearing the entry lane(s). The presence of a splitter island at roundabout approaches encourages a two-stage pedestrian crossing, a process in which each direction of vehicular travel is crossed independently. Consequently, there are four locations at which a pedestrian must evaluate gaps in vehicular traffic to determine crossing opportunities.

Given the particular traffic pattern at roundabouts, crossing from curb to splitter island, crossing from splitter island to curb, and crossing at entry versus exit approaches all are different for several reasons, including:

- Traffic is approaching from the left when crossing from the curb, but from the right when crossing from the splitter island;
- Traffic is moving only in front of the pedestrian when crossing from the curb (quiet behind the pedestrian), while it is moving both in front of and behind the pedestrian when crossing from

the splitter island; and

- Entering traffic is decelerating as drivers approach the yield line and circular roadway, while exiting traffic is accelerating as drivers exit the roundabout.

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

To figure out the minimum intersection sight distance, two parameters should be known. The first parameter is the critical headway, $t_{n,c}$, for the pedestrian. The critical headway describes the minimum amount of time necessary for a pedestrian to cross the roadway. The critical headway calculation is directly derived from the pedestrian analysis method covered in the two-way stop-controlled intersection methodology of the Highway Capacity Manual 2010 (TRB, 2010).

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

where,

L_n = crosswalk length for a specific traffic stream, ft;

S_p = average pedestrian walking speed, ft/s, could be measured in the field with a maximum value of 3.5 ft/s;

t_s = pedestrian start-up time and end clearance time, s (default is 2 seconds).

In the context of this analysis, the pedestrian start-up and end clearance time estimate should include any decision latency by a blind pedestrian. In field observations and direct comparisons of decision-making by blind and sighted pedestrians at CTLs (Schroeder et al., 2004), it is evident that a sighted person makes the crossing decision much more quickly compared to a blind person, who must often wait for the sound of a vehicle crossing the crosswalk to subside before being able to determine whether there is a gap, or there is another vehicle following the first.

The second parameter is the vehicle speed. The analyst can either measure or make an assumption about the speed, *V*, of vehicles along the approach of interest. For vehicles entering or exiting the roundabout, the speed can be determined using the speed prediction models presented in the previous section.

Using the speed (*V*) and critical pedestrian headways ($t_{n,c}$), the length of the conflicting vehicle paths (d) are calculated using the equations below. The different vehicle paths are shown graphically in Figure 5-3.

$$d_1 = (1.467)\,(V_{1,entering})\,(t_{1,c})$$
$$d_{2,e} = (1.467)\,(V_{2,entering})\,(t_{2,c})$$
$$d_{2,c} = (1.467)\,(V_{2,circulating})\,(t_{2,c})$$
$$d_{3,e} = (1.467)\,(V_{3,entering})\,(t_{3,c})$$
$$d_{3,c} = (1.467)\,(V_{3,circulating})\,(t_{3,c})$$
$$d_4 = (1.467)\,(V_{4,entering})\,(t_{4,c})$$

where,

d_1 = distance along entry leg upstream of the entry crosswalk for crossing from curb, ft;

$d_{2,e}$ = distance along previous entry upstream of the exit crosswalk for crossing from island, ft;

$d_{2,c}$ = distance along circulating lane upstream of the exit crosswalk for crossing from island, ft;

$d_{3,e}$ = distance along previous entry upstream of the exit crosswalk for crossing from curb, ft;

$d_{3,c}$ = distance along circulating lane upstream of the exit crosswalk for crossing from curb, ft;

d_4 = distance along entry leg upstream of the entry crosswalk for crossing from island, ft;

$V_{n,stream}$ = design speed of conflicting movement, mph;

$t_{n,c}$ = critical headway required by a pedestrian crossing a specific traffic stream, depends on the number of lanes and lane width.

Once the minimum distance, *d*, is determined for all possible conflicting movements, the designer should plot the distance along the actual vehicle path that is driven (i.e. the fastest path). Figure 5-3 shows the necessary sight distance, *d*, for each crossing location at the entry and exit of a roundabout. Note that the length of each *d* may be longer or shorter than shown relative to the roundabout geometry, depending on the speed and critical headway times used in the calculation.

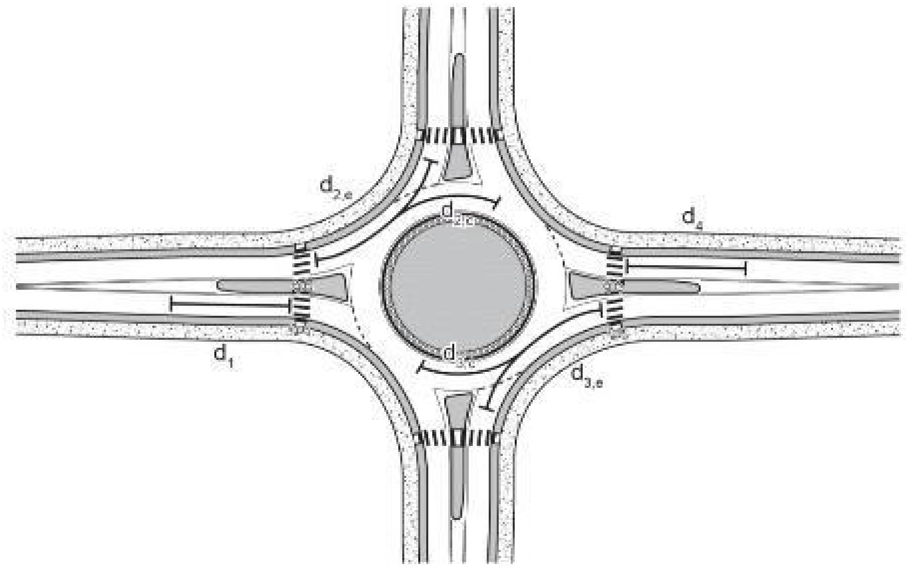

Figure 5-3: Minimum Sight Distance along the Actual Vehicle Path for Roundabouts

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

After plotting the distance from the pedestrian location, the sight triangle is determined as shown in Figure 5-4. Any sight obstruction should be eliminated from the sight triangles for better pedestrian visibility and enabling pedestrians who are blind to hear approaching vehicles more clearly.

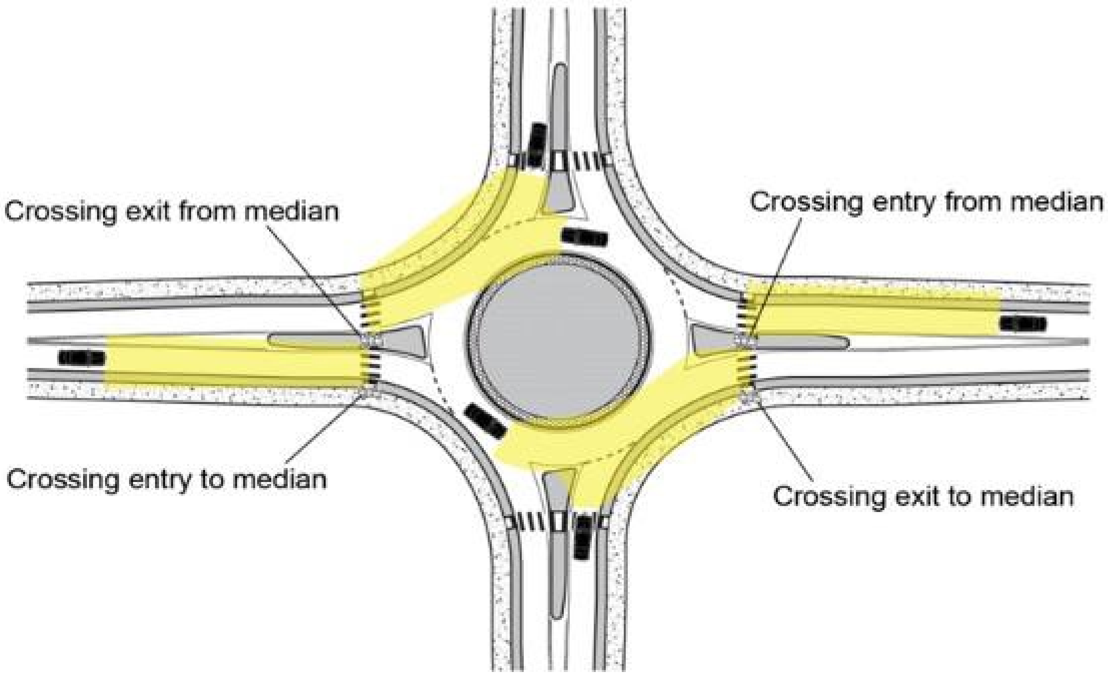

Figure 5-4: Pedestrian Sight Triangles for each Crossing Location (Sidewalk and crosswalks will be added to this figure)

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

For each entry and exit approach to a roundabout, three traffic streams should be checked that correspond to the pedestrian crossings of a roundabout:

1. ***Entering stream,*** which is composed of vehicles approaching the roundabout and not yet circulating. The speed for this movement can be approximated using the fastest path methodology for the entry path R1 as presented in NCHRP Report 672.
2. ***Exiting stream, adjacent approach,*** which is composed of vehicles that enter the roundabout at the adjacent (counterclockwise) approach and exit at the approach of interest. The speed for this movement can be approximated based on the right turn path radius R5 in NCHRP Report 672.
3. ***Exiting stream, circulating***, which is composed of vehicles that enter the roundabout prior to the immediate upstream entry and are thus completing either a through or left-turn maneuver prior to reaching the exit crosswalk. The speed for this movement can be approximated by taking an average of the radius terms R_2, R_3, and R_4 as an approximation, with the exiting speed in most cases limited by acceleration from circulating speeds (see NCHRP Report 672 for further discussion).

5.2.3 Crossing Sight Distance at Channelized Turn Lanes

Pedestrians crossing at CTLs are conceptually similar to crossing scenarios at roundabouts. Depending on the geometry and lane configuration of the intersection adjacent to the channelized turn lane, the facility may either perform similar to an entry (CTL with downstream yield control) or an exit approach of a roundabout (CTL with a downstream acceleration lane).

To make a safe crossing at a CTL, a pedestrian must consider the vehicular traffic approaching the CTL and attempting to complete the right-turning movement. At CTLs, the pedestrian is either crossing from the splitter island to the curb (scenario 1) or from the curb to the splitter island (scenario 2).

Similar to the roundabout methodology, the length of the traffic stream for approaching vehicles is calculated along its path (*d*) to determine how each sight triangle will be bound. Figure 5-5 shows the length of each path as it relates to each potential pedestrian crossing location. The figure shows the two locations at which the pedestrian must assess vehicular traffic in order to determine whether a safe crossing can be made. Note that the two crossing points are shown on different approaches for simplicity only.

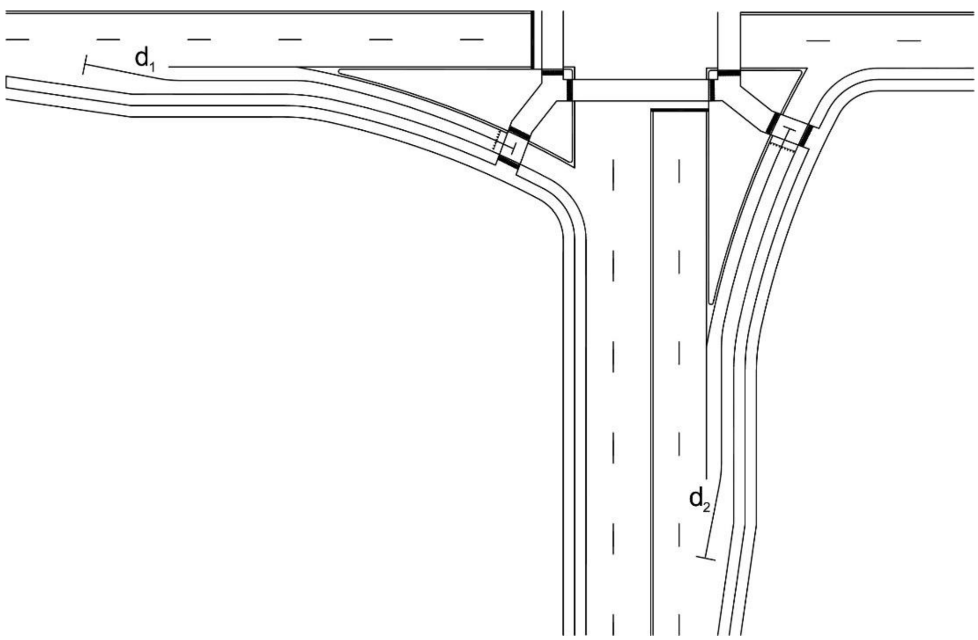

Figure 5-5: Minimum Sight Distance along the Actual Vehicle Path for CTLs

> *This figure shows a schematic of a CTL with calculated sight distances drawn for both crossings from the curb and crossings from the splitter island.*

As with the case of roundabouts, sight triangles bound by non-linear conflicting paths must be determined to provide adequate sight and auditory distances. Figure 5-6 shows the sight triangles associated with each crossing scenario.

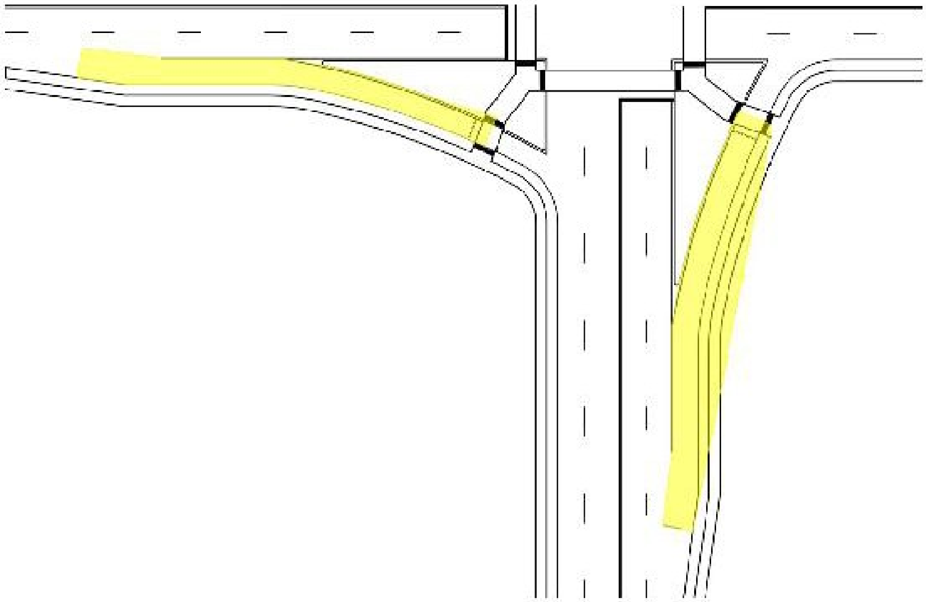

Figure 5-6: Sight Triangles Associated with Crossing Locations at CTLs

This figure shows a schematic of a CTL with estimated sight triangles drawn based on the calculated sight distances. Sight triangles are drawn for both crossings from the curb and crossings from the splitter island.

Consistent with the roundabout methodology, the two parameters of critical headway and vehicle speed should be measured or calculated. As stated in the prior section on roundabouts, the critical headway for a pedestrian crossing a traffic stream is based on the amount of time needed for a pedestrian to safely cross a specific traffic stream, plus a buffer time of 2 seconds. The critical headway calculation is consistent with the description above for roundabouts.

Once adapted to channelized turn lanes, the length of the conflicting vehicle paths (*d*) are calculated using the equations below.

$$d_1 = (1.467)\ (V_1\text{, entering})\ (t_{1,c})$$

$$d_2 = (1.467)\ (V_2\text{, entering})\ (t_{2,c})$$

where,

d_1 = distance along approach upstream of crosswalk for crossing from curb, ft;

d_2 = distance along approach upstream of crosswalk for crossing from island, ft;

$V_{n,stream}$ = design speed of conflict movement, mph;

$t_{n,c}$ = critical headway required by a pedestrian crossing a specific traffic stream, s, depends on the number of lanes and lane width.

5.3 Gap Opportunity Model

The availability of crossable gaps can be estimated using traffic flow theory concepts based on traffic volume and an assumed headway distribution. Assuming random arrivals, the analyst can use the negative exponential distribution to estimate the probability of observing a time-headway greater than t_c seconds

(May 1990). The term t_c in this case corresponds to the critical gap needed for a pedestrian to cross the street, measured in seconds. This equation assumes random arrivals of vehicles. For non-random arrivals, including platooning effects from upstream signals, other distributions are available (May 1990). The use of this equation for estimating the probability of crossable gaps for pedestrians was first introduced by Schroeder and Rouphail (2010) for estimating pedestrian delay at roundabouts, and was also referenced in NCHRP Report 674. Equation 1 shows the equation that can be used to estimate the probability of encountering a gap greater than the critical gap.

Equation 1: Estimating P(CG-Opp) from Traffic Flow Theory (May 1990)

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

where,

t_c = critical headway for crossable gap (sec.)

t_{avg} = average headway, defined as t_{avg}=(3,600sec/hour) / (V vehicles/hour)

In the absence of pedestrian platoons, the critical gap for pedestrians can be calculated by equation 2 following the pedestrian delay methodology at two-way stop-controlled intersections in the 2010 Highway Capacity Manual (TRB, 2010).

Equation 2: Pedestrian Critical Gap after HCM2010 Chapter 19

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

where,

L = crosswalk length (ft)

S_p = average pedestrian walking speed (ft/s) default = 3.5ft/s, and

t_s = pedestrian start-up and clearance time (s), default = 2s.

Using the above relationship, the probability of observing a crossable gap in a stream of 400 vehicles per hour at a 14-foot lane at a roundabout (or a CTL) and a corresponding critical headway of t_c=14/3.5+2=6 seconds is:

$$P(CG - Opp) = P(headway \geq 6\text{sec.}) = e^{-\frac{t_c}{t_{avg}}} = e^{-\frac{6}{9}} = 51.3\%$$

As an alternative to this theoretical estimation of the availability of crossable gaps, an analyst may be able to measure an empirical headway distribution, or develop such distribution from simulation.

The gap opportunity model was tested against field data collected at roundabouts and channelized turn lanes in this project. These data points are plotted against the volume of traffic and compared to the theoretical model. For more accurate results, only sites which had a total of more than ten available gaps were compared to the model since that represented a better sample size. The results are shown for two-lane roundabouts in Figure 5-7 and for channelized turn lanes in Figure 5-8. Calculated R-squared for the models are 0.59 and 0.23 respectively. The critical headway for crossable gap used for a two-lane roundabout entry and exit was calculated as 10 sec and for channelized turn lanes was calculated as 7 sec using the guidance above.

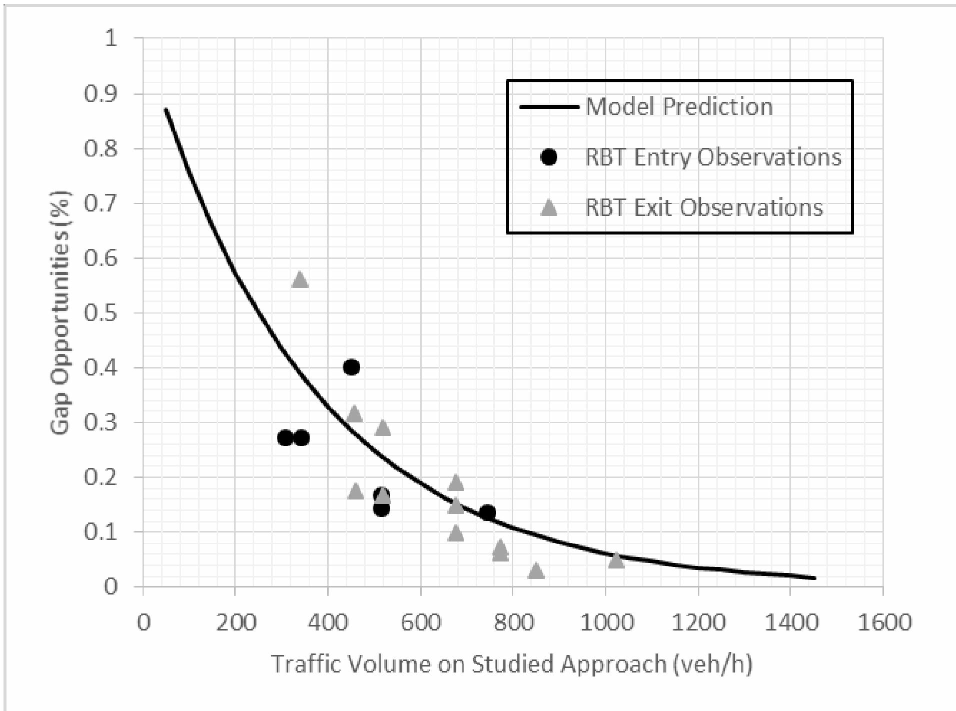

Figure 5-7: Gap Opportunity Validation for Roundabout Entry and Exit

The figure shows a data plot with traffic volume on the studied roundabout approach (in vehicles per hour) on the x-axis and gap opportunities (in %) on the y-axis. Three data series are plotted. The first series plots the predicted rate of gap opportunities as a solid line. The remaining two data series show field measured data for roundabout entries (gray filled triangles) and roundabout exits (black filled circles)

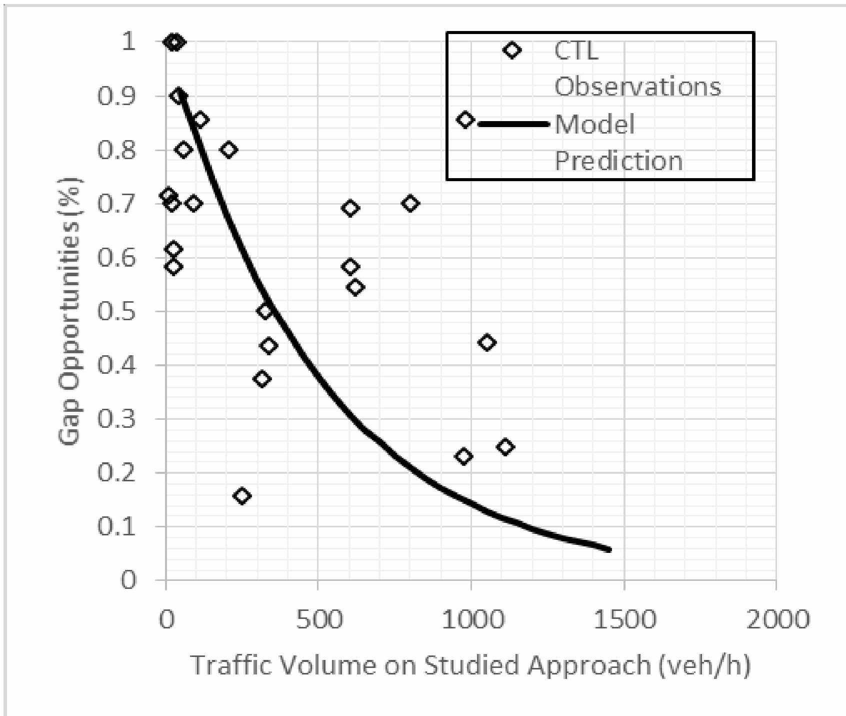

Figure 5-8: Gap Opportunity Validation for Channelized Turn Lanes

The figure shows a data plot with traffic volume on the studied roundabout approach (in vehicles per hour) on the x-axis and gap opportunities (in %) on the y-axis. Two data series are plotted. The first series plots the predicted rate of gap opportunities as a solid line. The other data series show field measured data for channelized turn lanes (black non-filled diamonds).

From Figure 5-7, it can be concluded that the theoretical model works well for roundabout entry and exits, which is confirmed by the reasonable R-Square value of 0.59. One outlier site in Greenbelt, MD was removed, because of the site's proximity to a metro station, which resulted in high vehicle platooning depending on the arrival and departure of trains at the metro station. That site consistently showed higher availability of gap opportunities than predicted by the model. Analysts should consider this when applying the model for roundabouts where vehicle arrivals may not be random, for example due to upstream signals.

For channelized turn lanes, Figure 5-8 shows that the theoretical model works for low volumes of traffic. At higher volumes (more than 500 vehicles/hour) the model appears to underestimate the availability of gap crossing opportunities. This could be the result of vehicle platooning from upstream signals and due to blockage. Hence, this model can only estimate crossing opportunities for random arrivals of vehicles and does not take into account the platooning effect that can be caused at higher volumes.

5.4 Yield Opportunity Model

The probability of encountering a yield opportunity is a function of different variables such as driver courtesy, potentially explained by factors such as making eye contact and other nonverbal communication between driver and pedestrian. It is also dependent on the geometry of the site, particularly the resulting vehicle operating speeds. More yields are expected where vehicle speeds are low and where drivers expect the presence of pedestrians, including university campuses and downtown areas.

Most field studies estimate the probability of yielding based on the number of vehicles that could have yielded, P(Yield). Note that this is different than the probability P(Y-Opp) used in here, which is calculated on the basis of all encountered vehicles. The latter term is thus a better representation of the yield encounter rate that a pedestrian is likely to experience. A reasonable approach for estimating P(Y-Opp) from P(Yield) is to subtract the probability of crossable gaps from the total number of vehicle events, as was illustrated in NCHRP Report 674 (see Equation 5-1):

Equation 5-1: Estimating Yield Opportunities from Yield Probabilities

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

This approach assures that the sum of $P_{Y\text{-}Opp}$ and $P_{CG\text{-}Opp}$ is less than or equal to 1.0 as is required by definition.

The team developed models that predict driver yielding behavior, P(Yield) at midblock crossings using logistic regression models from earlier studies (Schroeder 2008; Schroeder and Rouphail, 2011b), and work was recently completed on expanding the yielding prediction models to application for multi-lane roundabouts (Salamati et al., 2013).

The modeling of driver yielding behavior in these earlier studies showed several factors with a significant effect on the likelihood of yielding:

- Drivers that exit the roundabout have lower likelihood of yielding to a pedestrian than drivers entering the roundabout.
- At the exit leg of the roundabout, drivers who are turning right from the adjacent leg to the approach where the pedestrian is standing have lower propensity of yielding to pedestrians than drivers who are exiting from other directions.
- Drivers tend to yield more often to a pedestrian who is carrying a white cane compared to a sighted pedestrian.
- Drivers located in the far lane relative to the pedestrian location have lower likelihood of yielding to a pedestrian standing at the curb than a driver located in the near lane.
- As the speed of the vehicle entering or exiting the roundabout increases, the likelihood of driver yielding decreases.

The yield model development in this project used a total of 55 data points for two-lane roundabouts from nine states in the United States. There was not sufficient data available to develop a separate yield model for single-lane sites. From the data, multivariable linear regression models were generated to predict driver yielding rates to “blind” and “sighted” pedestrians at two-lane roundabouts in nine U.S. states. Statistical testing showed no significant difference between yielding rates to “blind” and “sighted” pedestrians, and as such final models were created through manual selection informed by full modeling efforts and correlation analysis using the dependent variable of interest, driver yielding rate to all pedestrians (YIELDR).

Several models were tested that focused on geometric and behavioral predictors for driver yielding behavior. The final selected model with the highest adjusted R^2 value includes fastest path radius and RRFB as explanatory factors for driver yielding behavior (Table 5-3).

Table 5-3: Recommended Model to Predict Yielding Rates to Pedestrians

	YIELDR Regression Coefficient	Std Error	p	95% Conf Interval	
RDS	-0.065	0.011	0.000*	-0.088	-0.042
RRFB	11.947	6.619	0.077**	-1.335	25.229
Constant	82.535	6.057	0.000	70.380	94.690
Prob > F	0.000				
R^2	0.392				
Adj. R^2	0.369				

**p*<0.05, ***p*<0.10

The final model to predict yields is also shown in Equation 5-2, and is a function of *approach fastest path radius (RDS)* and the *presence of an RRFB* at the approach. The fastest path radius (in ft.) is a continuous variable, and RRFB is a binary variable that is 1 if a roundabout approach is equipped with RRFB.

Equation 5-2: Estimating Probability of Yielding

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

The model predicts a base yield probability of 82.6%, which is reduced by 6.5% for each one hundred foot increase in the fastest path radius. The presence of an RRFB increases the yield probability by 11.9% after controlling for radius. The model has been calibrated from data at two-lane roundabouts only. It is expected, that yield rates at single-lane roundabouts are higher than the estimate from Equation 5-2, while yield rates at three-lane roundabouts are lower.

It is noted that the difference between roundabout entry and exit does not show up as a variable in the model, even though previous research found those to have significantly different yielding rates. In the current yield model the RDS variable accounts for these differences, with exit legs oftentimes having faster radii (and thus less yielding) than entry legs. This effect of fastest path radius is graphically illustrated in Figure 5-9.

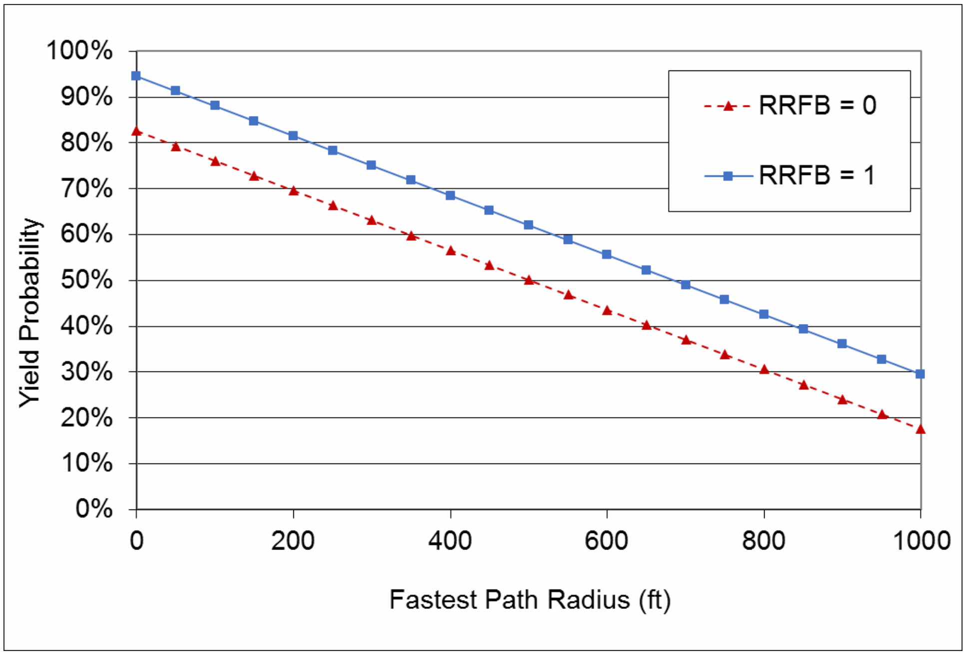

Figure 5-9: Graphical Representation of Yield Probability Model

5.5 Gap Utilization Model

This model describes the gap acceptance behavior by blind pedestrians at roundabouts and intersections with CTLs. It is hypothesized that the gap utilization rate is primarily a function of the size of the available gaps, and further that gaps needed by blind travelers are likely to be longer than those needed by sighted pedestrians (as described in the gap opportunity model). This corresponds to the rate of gap utilization being lower for blind travelers than for sighted travelers, given the same opposing traffic stream.

For blind pedestrians, gap utilization rates lower than 100% have been observed in research (NCHRP 674). Even if a gap is theoretically large enough to cross, there is a variety of factors that may contribute to gaps not being utilized, including added decision latency time (time between previous car and being ready to step into the roadway) and, most importantly, noise sources. The gap utilization adjustment is a way to account for these effects in an aggregated format by reducing the overall probability of crossable gaps calculated above.

Gap opportunity utilization is estimated from the average gap opportunity utilizations observed at study locations and are shown in Table 5-4.

Table 5-4 Estimated Average Gap Utilization for Blind Pedestrians

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

There is presently insufficient data in the literature to derive more sophisticated gap utilization models, but analysts are encouraged to use local data or estimates should those be available. The observed averages and standard error of gap utilization are shown graphically in Figure 5-10.

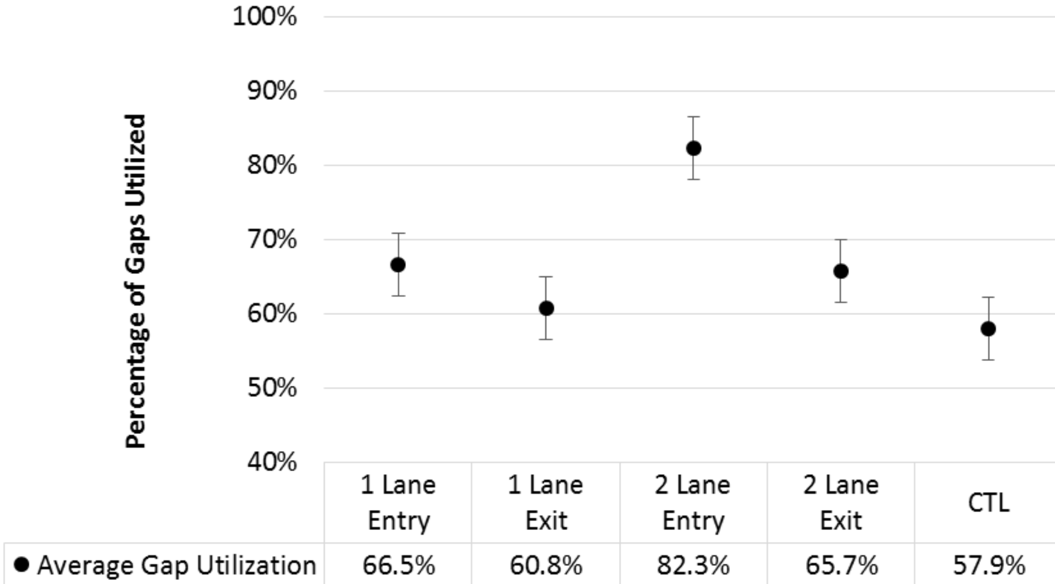

Figure 5-10: Graphical Presentation of Average Gap Utilization Rates

In addition to this variability by site geometry, it is emphasized that the gap utilization statistics further show a large range of values across study participants making it difficult to generalize for the entire population of blind pedestrians. If a user chooses to apply the average utilization rate, higher delays (due to lower utilization rates) can be expected for half of the population of blind travelers.

5.6 Yield Utilization Model

This model evaluates the rate of utilization of yield opportunities. It is hypothesized that most sighted pedestrians would accept most or all yield opportunities. Their rates of utilization for those events would therefore be assumed to equal 1.0. For blind pedestrians, yield utilization rates much lower than 100% have been observed in NCHRP 674, as well as in prior studies. Differences between individuals (including hearing differences) and unique acoustic characteristics of different sites are expected to affect these rates.

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

Table 5-5 Estimated Average Yield Utilization for Blind Pedestrians

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

The table shows average yield utilization rates for all roundabout sites in the range of 60-80%. For CTLs, the yield utilization was found to be much lower on average at around 35%, which is likely explained by increased background noise at many CTL locations. There is presently insufficient data in the literature to derive more sophisticated yield utilization models, but analysts are encouraged to use local data or estimates should those be available. The observed averages and standard error of yield utilization are shown graphically in Figure 5-11.

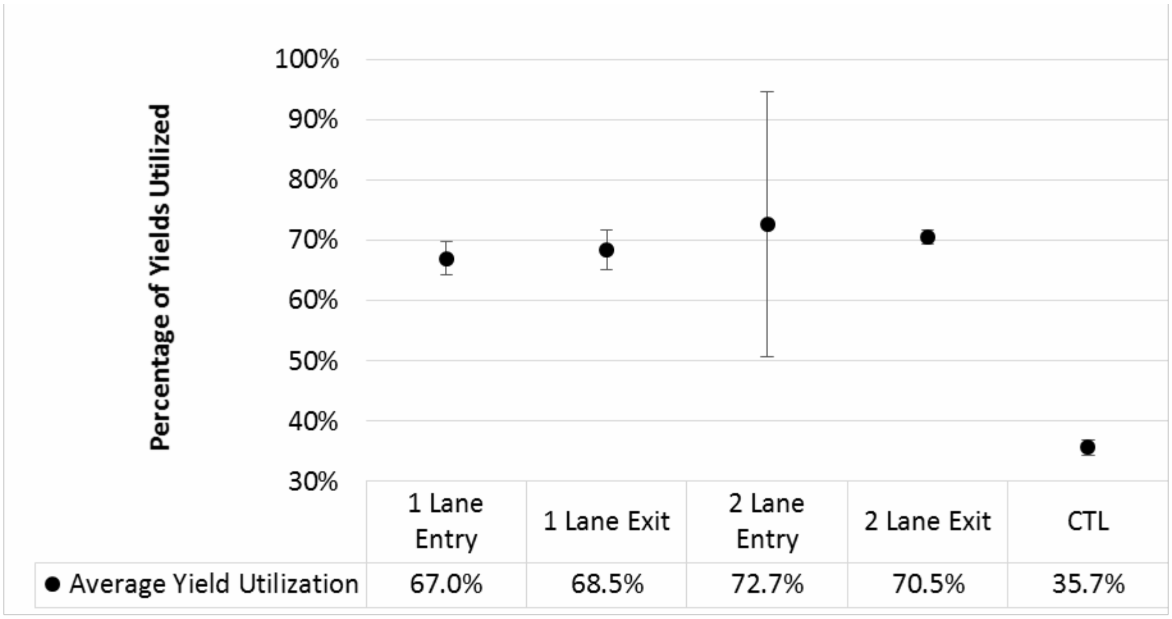

Figure 5-11: Graphical Presentation of Average Yield Utilization Rates

The statistics further show a large range of values across study participants, making it difficult to generalize for the entire population of blind pedestrians. If a user chooses to apply the average utilization rate, higher delays (due to lower utilization rates) can be expected for half of the population of blind travelers.

5.7 Audible Environment and Noise Effects

A key component of accessibility for a pedestrian who is blind is the availability of adequate audible cues to assure that a blind traveler can independently navigate the roundabout or CTL. The availability of audible cues is related to the presence of noise in the vicinity of the site, as well as obstacles that may interfere with the ability to clearly hear approaching vehicles. Such obstacles may include signs, poles, or landscaping, which may impact audibility in a matter similar to their impact on sight distances. However, in some cases obstacles may improve audibility. For example, heavy landscaping in the splitter island may help separate audible cues from the two directions of traffic, and thus enhance audibility of traffic for a blind pedestrian waiting on the splitter island (NCHRP Report 674).

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

5.7.1 Location of Crosswalk Relative to Noise Sources

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

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

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

5.7.2 Considering Curvature and Directionality of Traffic

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

5.7.3 Absolute and Relative Noise Levels

One key principle in acoustics research is the difference between absolute and relative noise levels. Research on the ability of blind travelers to identify quiet hybrid vehicles, as well as internal combustion engine vehicles, was shown to be highly correlated to the level of ambient noise (Wall Emerson et al, 2015). In other words, even a “quiet” vehicle can be audible at low ambient noise levels. Similarly, even a “loud” vehicle can be difficult to hear when the level of background noise is elevated. Research has shown that much of the noise generated by vehicles is tire noise, thus vehicle sound is related not only to the type of vehicle, but also its speed.

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

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

5.7.4 Impact of Grades

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

5.7.5 Location and Separation of Traffic Control Devices

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

The MUTCD provides specifications for installation of APS devices at signals. Two APS devices on the same corner should have a minimum separation of 10 feet, and have a rapid tick/tone walk indication. If it is not possible to achieve the minimum separation, the walk indication should be a speech message, and additional features should inform users which crossing the walk indication is for. This guidance applies at any location where APS are installed.

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

5.7.6 Impacts of Landscaping and the Built Environment

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

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

5.8 Delay Model

Previous research showed a link between pedestrian delay and probability of crossing at a crosswalk. The probability of crossing at a crosswalk, P(Cross), is described as a function of the probability of yielding, P(Y), the probability of yield utilization, P(GO|Y), the probability of encountering a crossable gap, P(G), and the probability of utilizing that crossable gap, P(GO|G):

$$P(Cross) = P(Y)*P(GO|Y) + P(G)*P(GO|G)$$

The team was successful in developing models to predict pedestrian delay at single-lane roundabouts, multi-lane roundabouts, and intersections with CTLs as a function of P(Cross). This allows analysts to estimate pedestrian delay for new sites if the input variables are known (Schroeder and Rouphail, 2010). Since the models are sensitive to the utilization measures, the delay can be distinguished between blind and sighted pedestrians, who may be presented with the same gap and yield opportunities, but have different rates of utilizing these opportunities.

Three separate models are developed for single-lane CTL approaches, single-lane roundabout approaches, and two-lane roundabout approaches. Pedestrian delay for single-lane CTL approaches is predicted as shown in Equation 5-3 as a function of *P(Cross)*. In the development of the CTL model, four studied sites in Tucson, AZ were excluded from the analysis, as these all resulted in very low delays of approximately five seconds on average, and did not follow the general data trends in the remaining nationwide sample of sites.

Equation 5-3: Calculating Pedestrian Delay for Single-Lane CTL Approaches

$$d_p = 10.75 - 9.95 * LN(P_{Cross})$$

Pedestrian delay for single-lane roundabouts is predicted as shown in Equation 5-4 as a function of *P(Cross).*

Equation 5-4: Calculating Pedestrian Delay for Single-Lane RBT Approaches

$$d_p = 9.37 - 9.78 * LN(P_{Cross})$$

Pedestrian delay for two-lane approaches (two-lane roundabouts) is predicted as shown in Equation 5-5 as a function of *P(Cross)*..

Equation 5-5: Calculating Pedestrian Delay for Two-Lane RBT Approaches

$$d_p = 6.14 - 8.53 * LN(P_{Cross})$$

The delay term, d_p, in Equation 5-3 through Equation 5-5 is measured in seconds per pedestrians. The equations are applied separately to each portion of the crossing, which in the case of a roundabout means the total delay is the sum of delay for the entry and exit legs.

The quantity increases with a decreasing probability of crossing, P_{Cross}, which in turn decreases with reduced availability and utilization of gaps and yields. As such, a low-volume site (lots of gaps) or a high-yielding site are expected to result in low delay, provided that utilization of crossing opportunities is adequate. As traffic volumes increase (reducing the availability of gaps), and as vehicle speeds increase (reducing the number of yields), the delay per pedestrian is expected to increase.

A graphical representation of the models developed for CTLs, single-lane RBTs, and two-lane RBTs is given in the following three figures (Figure 5-12, Figure 5-13, and Figure 5-14). For the CTL results in Figure 5-12, the four outlier sites from Tucson, AZ are shown separately from the nationwide sample of sites.

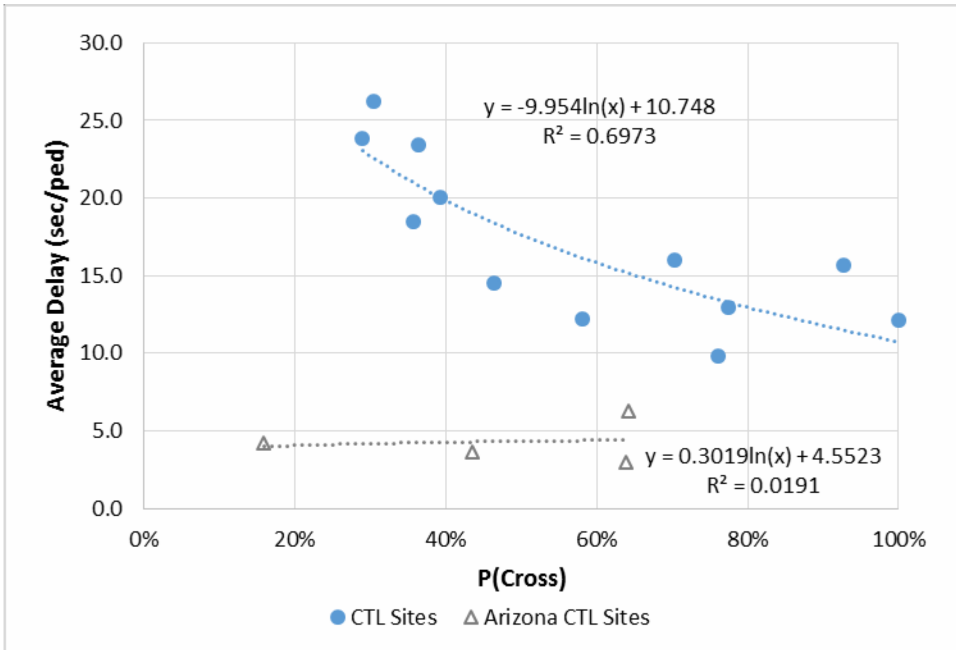

Figure 5-12: Graphical Representation of CTL Delay Model

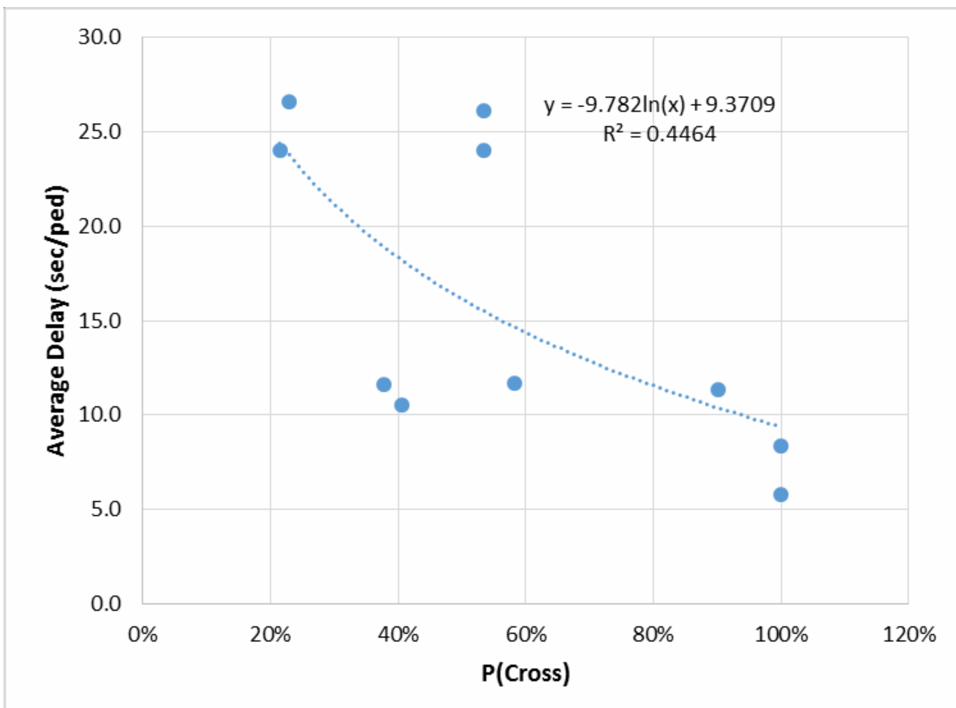

Figure 5-13: Graphical Representation of Single-Lane RBT Delay Model

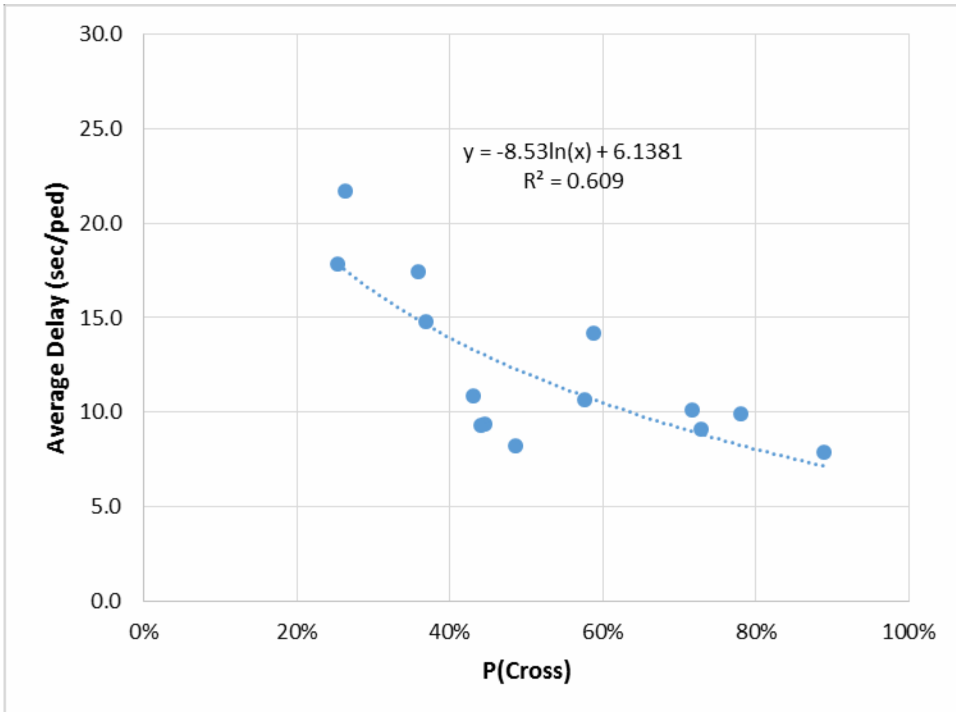

Figure 5-14: Graphical Representation of Two-Lane RBT Delay Model

As an alternative to this pedestrian delay methodology, the analyst may choose to refer to the method in the Highway Capacity Manual, or conduct a simulation study. However, it is emphasized here that the HCM method does not account for opportunity utilization of less than 100%. For simulation, a method for considering varying gap and yield availability and utilization distributions is described in Schroeder et al. (2013).

5.9 Risk Model

The third and arguably most critical accessibility performance check is the expected level of pedestrian risk. The level of risk is determined in field studies from intervention events by a Certified Orientation and Mobility Specialist, observer ratings, time-to-contact measurements, and video observations. These risk assessment factors are correlated to characteristics of the studied crosswalk to arrive at a risk prediction model. The model predicts the likelihood of a risky decision as a function of different variables.

Multivariable linear regression models were generated to predict the rate that blind pedestrians may make crossing decisions that result in intervention events. The resulting model to predict interventions includes noise level at the crosswalk (0 for low levels of noise and 1 for high levels of noise), average speed of the vehicle at the crosswalk (continuous variable for values greater than 10 mph) and sight distance (0 if pedestrian sight distance is provided and 1 if it is not provided).

The intervention model predicts the likelihood that a blind pedestrian makes crossing decisions which would have resulted in intervention. The intervention model, *P (INT)* is predicted as shown in Equation 5-6 as a function of *noise (NOISE)*, *average crosswalk speed (XSPD_AVE)*, and *sight distance (SIGHT_D)*. Variables NOISE and SIGHT_D are binary variables and equal to 1 if the noise level is high and the required crossing sight distance is not provided respectively. XSPD_AVE is a continuous variable and is defined for speeds higher than 10 mph.

Equation 5-6: Estimating the Probability of Interventions

P(INT)= 0.0629(NOISE)+ 0.0020*(XSPD_AVE)+ 0.0230*(SIGHT_D) – 0.0177*

Table 5-6 shows model development details for the proposed intervention model developed. The model includes variables NOISE (p=0.0393) , XSPD_AVE(p=0.067) and SIGHT_D (p=0.044). It is important to note that the model should only be used for speeds greater than 10 mph, which is the calibrated range of the observed data.

Table 5-6: Final Intervention Model

INT=	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
NOISE	0.0629	0.0118	5.34	0	0.0393	0.0866
XSPD_AVE*	0.0020	0.0011	1.87	0.067	-0.0001	0.0041
SIGHT_D	0.0230	0.0112	2.06	0.044	0.0006	0.0455
Constant	-0.0177	0.0204	-0.86	0.392	-0.0588	0.0234
Prob>F	0.00					
R-squared	0.558					
Adj. R-Squared	0.531					

Figure 5-15 plots the predicted intervention rates against the field observed intervention rates. A 45-degree line is drawn for reference to visually compare observed and predicted interventions.

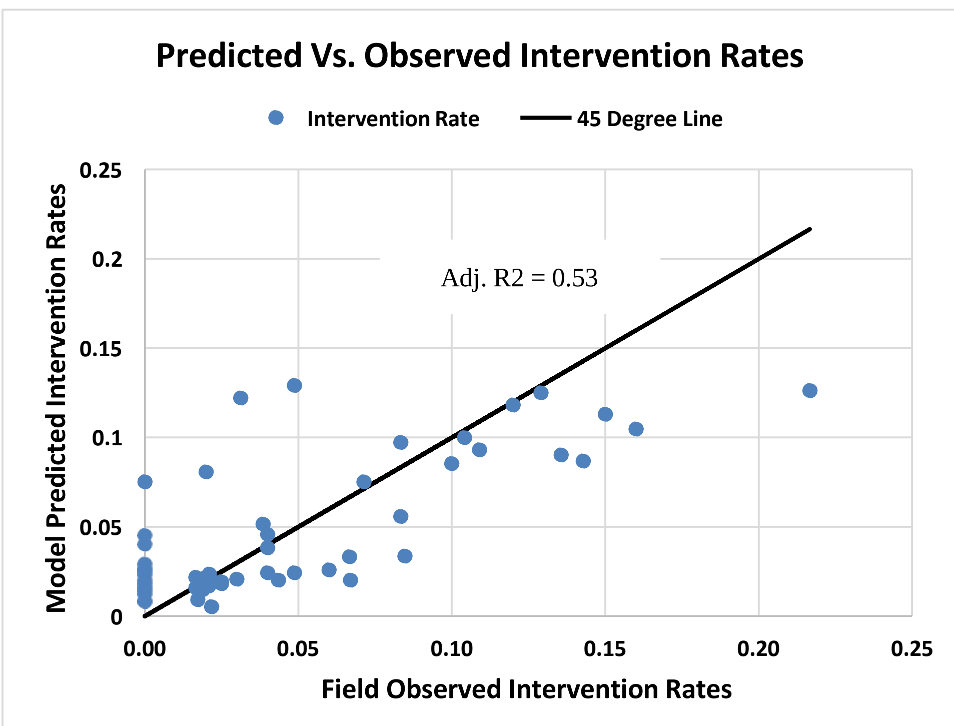

Figure 5-15: Plot of Predicted Intervention Rates vs. Observed Intervention Rates

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6 CONCLUSIONS

This document represents the final project report for NCHRP 03-78b: Guidelines for the Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities. The final report is a compendium to the primary deliverable of this research, the *Guidebook for the Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities.*

The guidebook is geared at providing useful and implementable guidance during the planning and preliminary design stage of a modern roundabout or channelized turn lane site. The guidebook aims to be a resource for engineers and planners developing and/or reviewing plans of designs that are about 30% to completion. Before that stage, designs may be too premature to have the necessary detail on proposed geometry and traffic characteristics; but after that stage, designs quickly become too fixed, including near-final placement of sidewalks, curb cuts, and signal poles. While the developed guidance is useful for existing sites and retrofit treatment installations, the focus is on establishing the accessibility of new sites due to the large variability of existing conditions at existing sites.

This final project report provides the documentation and added details for the research that resulted in the guidebook. As such, this report documents the literature review, data collection methodology, analysis results, modeling efforts, and other aspects of the project.

6.1 Implications for Practice

Roundabouts are increasingly being adopted by the transportation community in the US, due to their ability to process balanced and unbalanced traffic patterns, their aesthetic appeal, relatively low operating costs, and most importantly, their documented safety benefits (e.g., Rodegerdts et al., 2007; FHWA, 2000; Persaud et al., 2000). Similar to CTLs, there are concerns about the accessibility of roundabouts, particularly for pedestrians who are blind (US Access Board, 2003; American Council of the Blind, 2002). These accessibility challenges have been documented through extensive research by Guth et al., 2005; Ashmead et al., 2005; Schroeder et al., 2010; and Guth et al., 2013, among others.

Channelized turn lanes (CTLs) are a common treatment at signalized intersections, intended to allow heavy right-turning movements to bypass the main intersection. Crosswalks at CTLs are often unsignalized in the US, and pedestrians must therefore make crossing decisions based on their perception of an adequate gap or presence of a yielding vehicle. Accessible pedestrian signals (APS) or other audible devices are not available at most CTLs because they are unsignalized, but could be retrofitted and tied to the signal hardware at the main intersection. Accessibility challenges at intersections with CTLs have been documented by Schroeder et al., 2006, and Schroeder et al., 2010, among others.

Both intersection types can be associated with substantial benefits for both motorized and non-motorized traffic. CTLs can improve vehicle operations and safety at intersections, by providing added right turn capacity, by separating turning conflicts, or by accommodating larger design vehicles. Some CTL designs can also help pedestrians by shortening crossing distances and simplifying signal phasing, and help bicyclist, by reducing the potential for a “right hook” conflict between a right-turning vehicle and a through movement cyclist. As such, it is in the broader interest of the engineering and planning community to arrive at CTL designs that are accessible to all users, so that general CTL benefits can be achieved without compromising other road users.

Similarly, roundabouts have a safety track record with proven reductions in fatal and injury crashes over signalized intersections or two-way stop-controlled intersections. Roundabouts also bring operational benefits, especially in a 24-hour context where they can adapt to fluctuations in traffic volumes and changing traffic patterns. Roundabouts can also be very pedestrian and bicycle friendly, if traffic speeds are slowed down to levels comparable to cyclists, pedestrian crossings are placed in highly-visible and low-speed locations, and pedestrian decision-making is simplified to dealing with one direction of traffic at a time. Just as with CTL, roundabouts represent an intersection treatment that can enhance safety and serve all road users adequately if designed with all those users in mind.

The materials presented in this final report, and more importantly in the companion guidebook, are intended to provide engineers and planners with the tools and resources to consider pedestrians with vision disabilities in the design process, and understand the tools and principles for creating an accessible environment without losing the other benefits of a roundabout or CTL.

The guidebook developed in this research is not a prescriptive approach, nor is it a checklist of minimum requirements needed to meet ADA requirements. Rather, it is a *principles-based approach* that provides engineers and planners with an understanding of why certain characteristics of intersections can pose challenges to certain road users. The guidance is also *performance-based*, in that it produces measurable metrics and performance measures that can help quantify the accessibility performance, and allow analysts to weigh it against other performance measures.

With a principle and performance-based design philosophy, there is no "cookie cutter" solution, as each site brings unique challenges. But this philosophy also provides opportunities to arrive at accessible designs that are uniquely suited for each crossing. The design process is iterative, and a novice designer may take several iterations to arrive at a design that meets all objectives. But with experience, we are certain that the accessibility principles put forth in this research will become second nature, and equally familiar to designers as existing design principles and performance checks in documents like the FHWA Roundabout Guide.

Finally, this document and the guidebook are not standalone documents, in that they rely on the established practice and resources in publications like the FHWA Roundabout Guide, the AASHTO Green Book, the MUTCD, the Highway Capacity Manual, and others. This guidance is intended to supplement those resources, rather than replace them. Where applicable, this research borrows established methods and principles, but designers should always refer back to those documents. Orientation and mobility specialists, and the consumers they serve, can be an excellent resource for guidance about the challenges travelers without vision or with impaired vision face at roundabouts, CTL's, and other complex intersections without traffic controls. Designers, engineers and others in the transportation community are encouraged to use the many resources available to them for ensuring that roundabouts and CTL's are accessible to all road users, including those with visual impairments.

6.2 Summary of Findings

This research collected accessibility data at 12 channelized turn lane locations, and eight approaches to modern roundabouts, which each included separate study of the entry and exit legs. This resulted in a total of 28 crossings that were evaluated for their crossing and wayfinding performance.

In addition, this team gathered information in various prior research efforts, including NCHRP Project 03-78a, the Road Commission for Oakland County PHB and RRFB study, and FHWA Task Order project TOPR34 on "Evaluation of RRFBs at multi-lane roundabout approaches". The final results in this report and the guidance in the companion guidebook document combine results from all these research efforts, to get a comprehensive look at accessibility performance as a function of various design attributes.

In total, this and prior research evaluated 16 CTL and 58 roundabout sites. A "site" in this case, refers to one round of study at one approach to an intersection. A roundabout approach typically delivers two sites (one entry and one exit), and a before-and-after study similarly contributes to "sites". The studied sites were

- 16 approaches to channelized turn lanes in five different cities in four states. The CTL studies included various treatments, including raised crosswalks (5 sites), sound strips (2 sites), a stop sign (1 site), and a flashing beacon (1 site). The sites further varied with most having deceleration lanes

(15 sites), and some also having an acceleration lane (9 sites).

- 6 single-lane roundabout entries in 6 different cities in 4 states. Treatments tested at single-lane roundabout entries included raised crosswalks (1 site), and rumble strips (1 site).
- 6 single-lane roundabout exits in 6 different cities in 4 states. Treatments tested at single-lane roundabout exits included rumble strips (1 site), and RRFBs (1 site).
- 20 two-lane roundabout entries in 11 different cities in 11 states. Treatments tested at two-lane roundabout entries included pedestrian hybrid beacons (2 sites), RRFBs (13), raised crosswalks (1 site), and rumble strips (1 site).
- 20 two-lane roundabout exits in 11 different cities in 1 state. Treatments tested at two-lane roundabout exits included pedestrian hybrid beacons (2 sites), RRFBs (12), raised crosswalks (2 sites), and rumble strips (1 site).
- 1 three-lane roundabout entry and 1 three-lane roundabout exits, each studied three times with various treatments including no treatment (base case), RRFB, and RRFB plus a raised crosswalk.

The findings for the sites studied in this research are documented in Appendix D, with previously studied sites being summarized in NCHRP Report 674, the Oakland County Study Report, and the FHWA TOPR 34 Final Project Report on the RRFB Evaluation.

Based on the combined findings from the cited research, the following summary observations can be drawn. These findings were first noted in the FHWA TOPR34 final report, but were confirmed in observations in this research:

- An increase in the degree of curvature (smaller radii and shorter curves) correlates with a decrease in frequency of interventions. This trend is true for both roundabout entries and exits, as well as CTLs with the strongest correlation for exit legs. Roundabout exit legs, on average, tend to have smaller degrees of curvature (larger radii) than entry legs, and are on average associated with greater frequency of interventions. Predictive models for interventions were developed in this research as a function of vehicle free-flow speed, which in turn is a function of the degree of curvature as discussed below.
- An increase in the degree of curvature at the exit can be associated with improved visibility, and can facilitate the placement and visibility requirements for traffic signals, if those are part of the treatment solution for the roundabout. Providing clear line of sight between the pedestrian waiting area and approaching vehicles has further proven to be a very critical criterion for making a site accessible, which can for example be achieved by moving the exit portion of the crosswalk further away from the circulating lane.
- An increase in the degree of curvature (smaller radii and shorter curves) correlates with a decrease in the free-flow speed at the crosswalk. Free-flow speeds were generally higher at roundabout exit than at entry, which often correlates with general design and radius between the two. For CTLs, the free-flow speed is similarly correlated with radius. As curvature at entries and exits increase, free-flow speeds are expected to decrease. A predictive model to estimate FFS as a function of radius is found in the FHWA Roundabout Guide, and was found in this research to correlate well with field-measured free-flows speeds at crosswalks for both roundabouts and CTLs.
- A decrease in free-flow speed correlates with an increase in the probability that drivers yield to pedestrians. With generally higher free-flow speeds at roundabout exits than entries, the associated yield probabilities are also are lower at exits than entries. For CTLs, higher speeds are similarly linked to lower yielding. A predictive model was developed to predict yielding as the function of speed at the crosswalk, with the presence of an RRFB further increasing the yield probability.

From research done for FHWA, a study of the percent interventions suggests that a threshold may exist at a roundabout entry and exit radius of around 91.4 m (300 ft). Note that this radius is not the same as the central island radius/diameter, but rather the radius that controls the speed at the crosswalk. For roundabout entries, the R1 radius most closely describes this parameter, and at roundabout exits, the R3 term is a reasonable approximation (although speeds for vehicles may be limited by the speed in the roundabout and an acceleration constraint). For CTLs, the radius of curvature of the turn lane itself typically controls the speed at the crosswalk.

At entry crosswalks in the FHWA study of two-lane roundabouts, where all approaches had a radius of less than 91.4 m (300 ft), all percent interventions were less than 10 percent, and 9 out of 11 approaches had less than 5 percent intervention. This finding does not imply that all crosswalks with a controlling vehicle path radius of greater than 91.4 m (300 ft) are assured to be less accessible, nor that all crosswalks with a controlling vehicle path radius of less than 91.4 m (300 ft) are assured to be more accessible. But the findings may suggest, that 300 feet is a potential classifying threshold for distinguishing “small” and “large” radii. A 300-foot radius should generally be sufficient to accommodate most design vehicles, and is much larger than turns at traditional signalized intersections. But some multi-lane roundabouts and CTLs were found with radii significantly above this threshold, which is believed to contribute to accessibility challenges (particularly at roundabout exits).

From the same research, a threshold is also evident in the relationship between vehicular free-flow speed at the crosswalk and percent intervention. The observed percent interventions changes noticeably at a vehicular free-flow speed of around 35 km/h (22 mph). In this research, free-flow speeds were measured directly in the field with a radar device. For sites with free-flow speed below 35 km/h (22 mph), all but one location had less than 10 percent intervention, and 12 out of 14 had less than 5 percent intervention. For sites with free-flow speeds greater than 35 km/h (22 mph), 5 out of 7 had more than 10 percent intervention, and six out of seven had more than five percent intervention. This finding does not imply that all crosswalks with free-flow vehicular speeds greater than 35 km/h (22 mph) are inaccessible, nor that all crosswalks with free-flow speeds less than this value are accessible. But the findings may suggest, that 22 mph is a potential classifying threshold for distinguishing “low” and “high” speeds.

In addition to radius and speed, this research strongly suggests that factors such as ambient noise, pedestrian and crosswalk visibility, and vehicular lane utilization may have a greater influence in some cases than vehicular path radii and free-flow speeds. As such, sites with high ambient noise, poor visibility, and/or highly imbalanced lane utilization may prove to be inaccessible to blind pedestrians, even if vehicle speeds are low and the roundabout geometry features small radii. Nonetheless it appears roundabout designs with vehicle path radii less than 91.4 m (300 ft) and free-flow speeds at the crosswalk less than 35 km/h (22 mph) have a higher likelihood of being accessible than those with higher vehicular path radii and faster free-flow speeds.

From observations in this research, it was also evident that it is useful design practice to *separate the decisions points* for drivers, in terms of interacting with other drivers and pedestrians. At roundabout entries, general design practice places the crosswalk one vehicle length back from the circulating lane to provide that separation. In other words, the crosswalk should be placed where drivers can focus on interacting with pedestrians, and before having to judge gaps in the conflicting vehicle stream. The same has been observed for CTLs where sites with the crosswalk located too close to the downstream yield/merge point showed greater accessibility challenges. The team reasons that for sites with these *overlapping decision points* drivers tend to focus more on the conflicting traffic stream (to their left), and may not pay attention or react to a pedestrian waiting to cross the street (from the right). FHWA research in TOPR34 using eye-tracker data at roundabouts suggests that drivers tend to look more for gaps in the conflicting vehicle stream, and are less likely to see a pedestrian waiting on the right sidewalk, especially if the crosswalk is close to the circulating lane.

For roundabout lanes, a similar trend has been observed, where drivers who are still concerned with navigating the roundabout and the exit, are less likely to yield to pedestrians when the crosswalk is close to the circulating lane (FHWA TOPR34). This finding was based on observational field studies with pedestrians crossing at roundabouts, and was confirmed in eye-tracker experiments in the same research. The notion of separating driver-to-driver and driver-to-pedestrian decision points is a key design principle gleaned from this research.

While none of the trends above should be interpreted as being a direct causal factor, the correlations paint a useful picture of the types of variables associated with increased percent interventions at the studied sites. Conceptually, an increase in the degree of curvature (smaller radius), a reduction in free-flow speed, and an increase in yielding, are all associated with a reduction in percent intervention. The effect of traffic volumes is mixed, with higher traffic volumes at roundabouts being associated with a decrease in interventions at exit legs, but an increase for entry legs, likely due to an increased chance for multiple threat events with more vehicles. For CTLs, no effect of traffic volumes was found conclusively. In addition, other factors such as the ambient noise, visibility, lane utilization, and the local driver culture also appear to be important factors affecting percent interventions.

6.3 Treatment Effects

The various accessibility projects that form the basis of this work evaluated a range of treatments that are geared at enhancing accessibility, which fall in four broad categories:

1. Treatments geared at <u>reducing vehicle speeds</u> through geometric modifications, which includes speed humps, raised crosswalk, or geometric changes;
2. Treatments geared at <u>enhancing the visibility</u> of the crosswalk and alerting drivers, which includes RRFBs and other beacons;
3. Treatments geared at <u>providing additional audible information</u> to blind pedestrians, which includes the sound and rumble strips tested at CTLs; and
4. Treatments geared at <u>stopping traffic and creating crossing opportunities</u>, which includes pedestrian hybrid beacons and other pedestrian signals.

Some treatments fall into multiple categories, and therefore have combined effects. Sound strips for example may help alert drivers in addition to pedestrians and have a speed-reducing effect. Similarly, beacons and signals have to be outfitted with audible devices, which can enhance the available information to pedestrians, as well as assist with wayfinding.

In general, the treatments tested in this and prior research should be evaluated in the context of the accessibility evaluation framework. Rather than being thought of as a “one size fits all” or “cookie cutter” solution, each treatment serves a very specific purpose and should be targeted to address a specific shortcoming of a site. For example, if vehicle speeds are found to be too high (above 22 mi/h as summarized above), a raised crosswalk may be a suitable option to reduce that speed. This by now is the standard design treatment for CTLs in Boulder, CO, for example, and has also proven effective at multiple roundabouts tested in this research.

Similarly, beacon treatments may specifically target locations where visibility is poor and drivers may not be aware of the presence of pedestrians wanting to cross. However, as was found in the FHWA RRFB evaluation, a beacon like the RRFB alone is unlikely to greatly enhance accessibility for a site with very high design speeds. In those cases, a combination with a raised crosswalk, or a treatment that stops drivers with a red indication may be more appropriate.

All treatment effects are evaluated as part of the evaluation process outlined in the accompanying guidebook document. Their effectiveness is measured in terms of their effect on one or more of the inputs in the accessibility evaluation, which in turn may impact the final outcome and performance. For example, rather than describing a raised crosswalk in terms of its ability to reduce interventions or delay, it is evaluated first and foremost as a treatment that reduces vehicle speeds. Those reduced speeds in turn result in increased yielding and increased crossing opportunities, which are linked to reduced delay. Speed is also an input in the safety performance, and as such a raised crosswalk is expected to improve delay and risk as a consequence of its speed-reducing effects.

Finally, there are a host of other treatments that have not specifically been evaluated in this research, but that are likely to have beneficial effect. In general, considering treatments in light of the four categories and the effects in the overall evaluation process can help designers screen and weigh treatment options. As such, treatments like an advanced yield line at multi-lane approaches to reduce multiple threat events is likely beneficial at roundabouts, based on its effectiveness at midblock locations. Similarly, in-pavement flashing lights may be an alternative to an RRFB, or a speed bump may be considered as an alternative to a raised crosswalk with the same end result. So in addition to treatments tested in this research, designers should look to other literature and resources like the PEDSAFE tool for other ideas on treatments.

6.4 Wayfinding

The majority of the roundabout and CTL crossings under study were not found to reliably provide wayfinding information that could be expected to result in routinely safe and efficient crossing by blind pedestrians. While these findings are tentative, the diversity of the roundabouts and CTL's at which this was the case suggests that this is not something that can be ignored by designers who wish to design accessible intersections. Observations of the techniques and strategies used and the errors made by participants provide information about features and strategies that appear to provide useful wayfinding information. Three principal wayfinding tasks were explored in this research:

1) Determining the Crossing Location, including detecting the street,
2) Aligning to Cross (establishing a correct heading), and
3) Maintaining Correct Heading While Crossing (staying within the crosswalk).

The same tasks are necessary tasks for crossing in either direction from the island. Wayfinding on the islands was challenging for blind participants. There are many possible configurations, and design features are not consistent. Islands that are only delineated by pavement markings are not recognized at all by pedestrians who are blind.

Typical strategies for **locating a crosswalk** include continuing to the curb in the direction traveled on the approach sidewalk and using traffic stopped at the stop line as a cue to the crosswalk location. Because of the curvature of the sidewalk at roundabouts and CTLs, and the fact that the crossing point is often to one's side, even very experienced blind individuals such as many of our participants can find it difficult to recognize the desired crossing point. Features that seemed to help in determining the crossing location (locating the crosswalk) included: (1) grass or other landscape strip between sidewalk and curb, and (2) grass or gravel outside the crosswalk area, particularly on islands.

Features that didn't seem to provide adequate information to pedestrians who were blind in locating the crosswalk included paved or hardscape surfaces.

This research did not examine other cues that have been used for aiding nonvisual crosswalk location, such as guidance surfaces, as is used in Australia and other countries, and which pilot research at midblock crossings in Raleigh, NC showed to have a significant benefit to locating crosswalks. More research may provide additional treatments that could assist with this task.

Another important aspect of locating the crosswalk is recognizing the street edge. At most locations, detectable warning surfaces were installed to indicate the edge of the street at curb ramps. The detectable warning surface must extend the full width of area that is level with the street to provide an adequate warning. At the roundabout and CTL locations where detectable warnings were not installed or did not extend the full width of the level area, some research participants continued into the street without recognizing that they had done so.

When **aligning to cross**, blind participants were observed to, and reported themselves to, use a combination of cues, including underfoot surfaces and traffic movement. The alignment, relevant to the direction of travel on the associated crosswalk, of the approach sidewalk, the orientation of the detectable warning surface, the slope of the ramp, and the orientation of gutter/edge of the street are all cues that may be used by individuals who are blind. While these may not be consistent, they all contribute to the alignment decisions. Features that seemed to help in aligning to cross included having all wayfinding cues (approach direction, landscaping or edge of the sidewalk, the curb ramp slope, detectable warning surface, and edge of the street/gutter) aligned with the crosswalk direction or perpendicular to the crosswalk direction.

Features that appeared to provide inadequate or confusing alignment information included installing the various features mentioned so that they are not aligned with the crosswalk direction.

Without traffic traveling parallel to the crosswalk as they cross, blind pedestrians have few cues to help them **maintain the correct heading and stay within the crosswalk**. Short crossings allow less opportunity to veer from the beginning line of direction, so shorter distances (i.e. narrow lanes) may be an advantage.

Finally, pushbuttons for pedestrian signals, accessible pedestrian signals, RRFBs or other devices can provide very useful wayfinding information for all three wayfinding tasks. However, the devices must be outfitted with an audible output, and must be located close to the crosswalk they control in order to be useful to pedestrians who are blind.

6.5 Limitations and Future Research

Several limitations exist in this research, which are summarized below.

- Despite a much larger sample size compared to prior research, and especially NCHRP 03-78a, the sample of sites is still limited. Sites used were locations where treatments had been installed by local agencies and there was variability in how those treatments were installed. Most performance measures showed high variability, which made it difficult to clearly isolate effects of treatments and design characteristics. An in-depth study of one intersection type and one treatment at a time (similar to the FHWA RRFB study) is recommended for any future research looking to supplement these results.
- Additional testing with a red signal display (PHB or standard signal) and evaluation of more low-cost traffic calming treatments, such as raised crosswalks at two-lane roundabouts, are needed to increase sample size and build confidence in treatment effectiveness.
- From the data, it is evident that local context is very important for any accessibility evaluation. Driver culture, the level of expectation of pedestrians, enforcement, and education all appear to be key factors that impact driver behavior, yielding, and ultimately accessibility. As such, any generalization of the study results should be considered carefully within the local context of a site and region of the country.
- The analysis process developed in this research needs to be verified at additional sites not part of this study. Ideally, future research would build upon feedback and lessons learned from agencies and practitioners using the guidebook and final report to further enhance future documents. There is a need for training and technology transfer of the research results, to assure the guidance is applied correctly, and to help improve future revisions of these documents.
- The current deliverables are presented as standalone documents and not yet integrated with other guidance documents, including the FHWA Roundabout Guide.

- The focus of the guidebook is on the design of new facilities, and not on the execution and field installation of specific treatments. As such, there is a need to train field crews and inspectors to assure that intersections designed in accordance with this guidance are properly constructed.
- This report provides only limited information on education and training measures to assist blind travelers in successfully navigating unknown geometries at roundabout and CTL intersections. More work is needed in this area to try and standardize instruction and guidance provided to the travelers themselves. However, it is clear that training cannot resolve the problems of a design that does not provide adequate cues and information to an individual who cannot see.

7 APPENDIX A: WAYFINDING DATA DETAILS

This appendix presents the wayfinding method and the data collected at roundabouts and channelized turn lanes. Data were collected at roundabouts in Michigan, North Carolina, Ohio, and Maryland, and at channelized turn lanes in Colorado, North Carolina, Maryland, and Arizona. The data are presented, first, in the form of summary figures and, later, in the form of tables showing the results for individual wayfinding tasks at individual sites. The information is presented in this way in order to assist the reader to understand the general patterns obtained and the substantial variability in wayfinding performance across sites, and to allow the reader to understand the limitations of the research approach and related data.

7.1 Introduction

As noted in Section 4, above, the overall crossing task for blind pedestrians at roundabouts and channelized turn lanes consists of four major subtasks:

1. Determining the crossing location, including detecting the street.
2. Aligning to cross (i.e., establishing a correct initial heading) at a crosswalk that may or may not be aligned perpendicular to the sidewalk or in the same direction as the slope of the associated curb ramp.
3. Deciding when to cross in an environment of largely uninterrupted traffic flow, requiring the identification of appropriate gaps in traffic or crossing opportunities in front of yielding vehicles. When signals are provided, an audible message conveys to a blind pedestrian when the WALK sign is active.
4. Maintaining correct heading (staying within the crosswalk) during the entire crossing (e.g., in the case of a roundabout, until the splitter island or far curb is reached).

Three aspects of the crossing task are typically characterized as wayfinding tasks: determining the crossing location (finding the crosswalk), aligning to cross, and maintaining crossing heading. Errors in performing these tasks may lead to beginning the crossing outside the crosswalk area, crossing to the central island of a roundabout, or missing the island at a channelized turn lane. This can cause general confusion and disorientation for the blind pedestrian. Crossing at a location that is not within the crosswalk and where drivers are not expecting pedestrians can be a safety issue as well.

7.2 Method

7.2.1 Data Collection

A wayfinding study was performed at a subset of the project's roundabout and channelized turn lane crosswalks to determine error rates for the three major wayfinding tasks. We also recorded information, not summarized in this appendix, on the need for safety interventions by the orientation and mobility (O&M) specialist monitoring the trial and the amount of time taken to perform the wayfinding tasks. For each trial, a blind participant was guided by an O&M specialist to starting locations that varied from over 100 feet from the crosswalk to approximately 10 feet from the crosswalk. The participant was then asked to find the crosswalk, to align to cross, and to cross to the island when asked by the O&M specialist. In addition, the participant was asked to find the crossing starting location on the island and align for the second stage of the crossing. A trial ended after the alignment task on the island; the participant was not asked to complete the second stage of the crossing. Separate data were collected for wayfinding to the island and wayfinding on the island.

The sites varied widely in terms of characteristics that the team's O&M specialists hypothesized would provide useful wayfinding information. Because the wayfinding study was a component of a larger study whose principal goal was to evaluate crosswalk treatments' effects on the decision about when to cross (subtask 3 above), the choice of wayfinding sites were constrained by the choices made for the larger study.

The data-coding scheme is given in Table 7-1. The raw data codes represent what was actually measured while the analysis codes show how the raw data were combined to arrive at the error figures discussed in this appendix. For example, whereas we recorded the right or left direction of any initial alignment error, these leftward and rightward errors were combined to arrive at what this appendix discusses as "Initial Alignment Error." There were six major error criteria: 1) Missed Crosswalk Error, 2) Crosswalk Location Error, 3) Initial Alignment Error, 4) Excessive Time Error, 5) Crossing Ending Location Error, and 6) Intervention.

A missed crosswalk error indicated that the participant continued past the correct crossing location, the crosswalk, or did not walk far enough to find the crosswalk. Often, participants passed the crosswalk and turned around to search for it without any prompting by the O&M specialist. If the participant continued more than 20 feet past the crosswalk, the O&M specialist would intervene and tell the participant that they had passed the crosswalk. That was coded both as an intervention and a missed crosswalk error. For the raw data, Missed Crosswalk Error was coded as 1) "Did not miss the crosswalk," 2) "Missed the crosswalk, but corrected," or 3) "Missed the crosswalk." For the purposes of deriving an error rate, "Missed the crosswalk" was recoded as 1, and codes 1 and 2 were recoded as 0.

A crosswalk location error occurred when a participant aligned to cross outside the crosswalk lines. Crosswalk location error was coded as 1) "Within crosswalk," 2) "Outside crosswalk <5 feet," and 3) "Outside crosswalk >5 feet" for the raw data. Codes 2 and 3 were recoded as 1, and "Within crosswalk" was recoded as 0 for the analysis.

The initial alignment was recorded when the participant determined that they were aligned and ready to cross. The data coder, standing directly behind participants, observed their basic body and foot alignment and coded their alignment as within crosswalk or outside crosswalk presuming that they maintained their initial heading while crossing. If participants who maintained their initial alignment would complete their crossings outside crosswalk, the direction of misalignment, left or right was recorded. Initial Alignment Error was coded as 1) "Within," 2) "Left," and 3) "Right" in the raw data. Codes 2 and 3 were recoded as 1, and "Within" was recoded as 0 for the descriptive statistics analysis.

After the alignment was coded, the O&M specialist chose a safe time to cross and asked the participant to cross. The participants crossed independently using their initial alignment or crossing heading and typical cane skills. The data coder recorded the location where participants completed their crossings to the island in the same way as the Initial Alignment Error, as 1) "Within," 2) "Left," and 3) "Right" for the raw data. Codes 2 and 3 were recoded as 1, and "Within" was recoded as 0 to derive the Crossing Ending Location Error.

Excessive Time Error was initially intended as an efficiency measure, and was based on the amount of time in seconds taken for the entire wayfinding process, with a unique time for wayfinding to the island and wayfinding on the island to the second crosswalk starting location. This error is not included in the descriptive statistics because we could sometimes not control the variability in starting location/trial distance across sites.

There were several times when the monitoring O&M specialist might intervene during a trial. An intervention might be recorded if the participant passed the crosswalk, as noted before. Interventions also took place if the participant was beginning to cross into traffic at a dangerous place, such as aligning to cross the circulatory roadway toward the center island at a roundabout, or missing the island completely at a channelized turn lane. The O&M specialist did not typically intervene if the participant made an error but was not in danger. For example, some individuals ended their crossing several feet outside of the crosswalk and walked along the curb of the island in the street while looking for the cut-through area or curb ramp of the island, but vehicles were not close or were yielding until the person reoriented themselves. Intervention was coded as 1 if at least one intervention occurred during a trial, and 0 if no intervention occurred during a trial. For some participants, there were several interventions during a trial. Interventions occurred during 33 of the 243 total trials. The most interventions to occur in a trial was six, and the average number of intervention across all trials where interventions occurred was one.

Missing information was coded as 999, which was used, rarely, when a researcher failed to write down observations about a trial. The code 777 was used when a task was not performed due to circumstances such as participant confusion or safety concerns. There were times when the participant became so disoriented that the O&M specialist ended the trial. Some situations where this took place included an island at a channelized turn lane where the participant ended their first crossing outside the crosswalk and cut-through area and was unable to reorient on the island, thinking the cut-through pedestrian channel was the street. If a participant lined up to cross into the circulatory roadway at the roundabout, the O&M specialist would intervene and guide the person to the crosswalk. In that case the crosswalk location error and subsequent intervention was coded as "Missed the crosswalk" because the participant did not find the crosswalk location independently.

Error rates (dichotomous summary data) were calculated by dividing the total number of errors by the sum of errors and no errors for a given task. Error rates were summed by task for all roundabouts and for all channelized turn lanes. Error rates were also calculated separately for each roundabout and each channelized turn lanes. Table 7-1 shows the raw data codes entered during the experiment, which includes up to three key codes for each criterion. For analysis, all criteria were converted into a one/zero binary response, as summarizes in the "analysis codes" column.

Table 7-1: Wayfinding Data Codes Based on Error Criterion

Raw Data Codes		Codes	
1	**Missed Crosswalk Error**		
1	Did not miss	1	Missed
2	Missed but corrected	0	Did not miss and Missed but corrected independently
3	Missed		
2	**Crosswalk Location Error**		
1	Within CW	1	Outside <5' and Outside >5'
2	Outside <5'	0	Within CW
3	Outside >5'		
3	**Initial Alignment Error**		
1	Within	1	Left and Right
2	Left	0	Within
3	Right		
4	**Excessive Time Error**		
	Raw time in seconds		Raw time in seconds
5	**Crossing Ending Location Error**		
1	Within CW	1	Outside <5' and Outside >5'
2	Outside <5'	0	Within
3	Outside >5'		
6	**Intervention (any number per trial)**		
1	Yes	1	Yes
2	No	0	No
Missing information was coded as 999. *The code 777 was used when a task was not performed.*			

7.3 Results

7.3.1 Wayfinding to Island

Figures 7-1, 7-2, and 7-3 provide error rates for wayfinding to the island for all roundabout and channelized turn lane sites, and for roundabout and channelized turn lane sites by location. Table 7-2 provides detailed information on study locations and sample sizes for roundabout and channelized turn lane sites by intersection location.

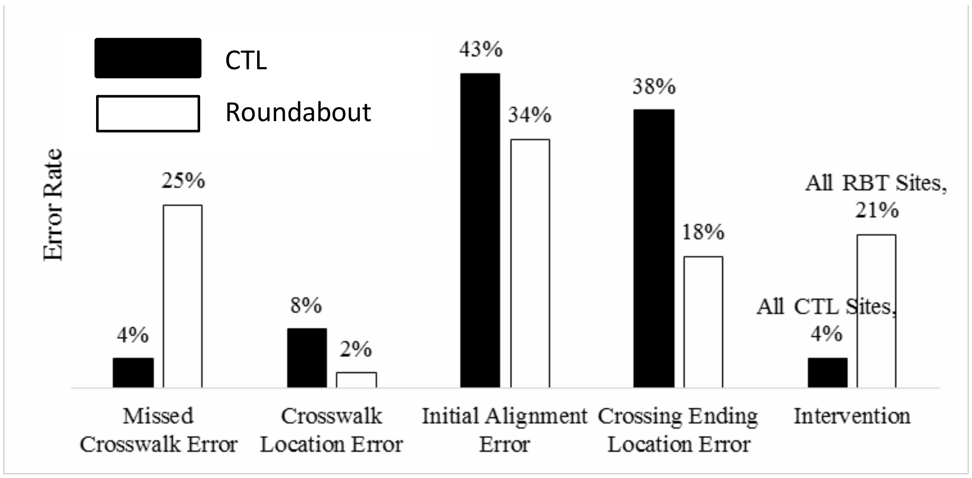


Figure 7-1: To Island Wayfinding Error Rates for All Roundabout and Channelized Turn Lane Sites

Bar graph shows the wayfinding error rates for crossings to the island for all sites. 4% missed crosswalk error was recorded at CTL sites and 25% missed crosswalk error for roundabout sites. Crosswalk location errors were 8% for CTLs and 2% at roundabouts. The initial alignment errors for were 43% and 34% for CTLs and roundabouts, respectively. Crossing Ending location errors were 38% at CTLs and 18% at roundabouts. Interventions occurred on 4% of trials at CTLs and 21% of trials at roundabouts.

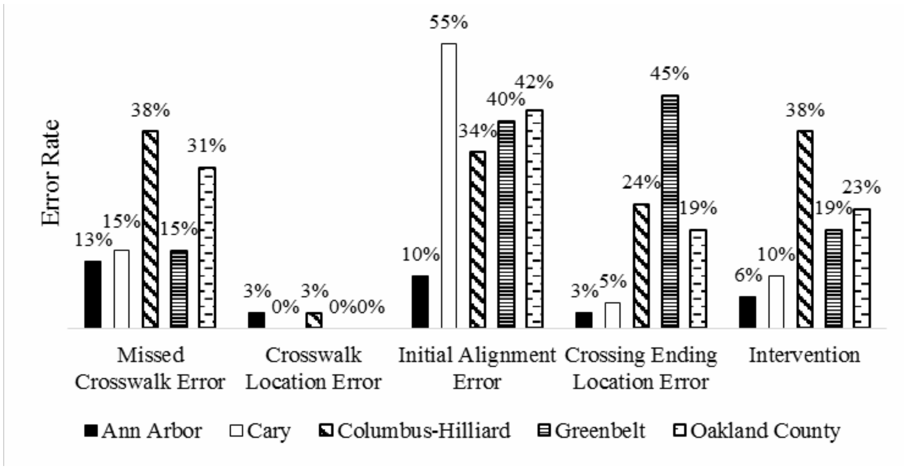


Figure 7-2: To Island Wayfinding Error Rates for Roundabout Sites

Bar graph shows the wayfinding error rates for each of the roundabout sites. For missed crosswalk, there was 13% error rate at Ann Arbor, 15% at Cary, 38% at Hilliard, 15% at Greenbelt and 31% at Oakland County. Crosswalk location errors were 3% at Ann Arbor and 3% at Hilliard and 0% at other sites. The initial alignment errors varied from 10% at Ann Arbor to 55% at Cary, with 34% at Columbus-Hilliard, 40% at Greenbelt and 42% at Oakland County. Crossing ending location errors were 3% at Ann Arbor, 5%at Cary, 24% at Columbus-Hilliard, 45% at Greenbelt and 19% at Oakland County. Interventions occurred on 6% of trials at Ann Arbor, 10% of trials at Cary, 38% of trials at Columbus-Hilliard, 38% of trials at Greenbelt and 19% of trials at Oakland County.

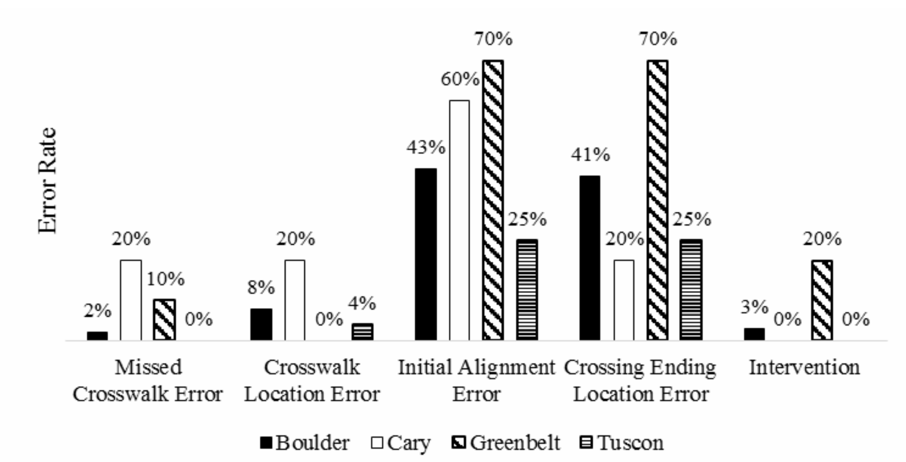


Figure 7-3: To Island Wayfinding Error Rates for Channelized Turn Lane Sites

Bar graph shows the wayfinding error rates for each of the CTL sites. For missed crosswalk, there was 2% error rate in Boulder, 20% at Cary site, 10% at Greenbelt, and 0% in Tucson. Crosswalk location errors were 8% at Boulder and 20% at Cary, 0% at Greenbelt and 4% in Tucson. The initial alignment errors were 43% at Boulder, 60% at Cary, 70% at Greenbelt and 25% at Tucson. Crossing ending location errors were 41% at Boulder, 20% at Cary, 70% at Greenbelt and 25% at Tucson. Interventions occurred on 3% of trials at Boulder, 0% of trials at Cary, 20% of trials at Greenbelt and 0% of trials in Tucson.

Table 7-2: To Island Wayfinding Locations and Sample Sizes

Site Name	Site Type	Intersection	Approach	Number of Subjects	Total Number of Observations for each task at each site
Boulder, CO	CTL	Arapahoe and Foothills SW	N/A	5	10
Boulder, CO	CTL	Foothills and Baseline NE	N/A	5	10
Boulder, CO	CTL	Foothills and Baseline SW	N/A	5	10
Boulder, CO	CTL	Canyon and 28th SW	N/A	5	10
Boulder, CO	CTL	Pearl and 28th NE	N/A	6	12
Boulder, CO	CTL	Pearl and 28th NW	N/A	5	10
Cary, NC	CTL	Kildaire Farm and Tryon W	N/A	5	10
Greenbelt, MD	CTL	Kenilworth and West NW	N/A	6	10
Tucson, AZ	CTL	Grant and Oracle NE	N/A	3 (Pilot subject omitted)	6
Tucson, AZ	CTL	Grant and Oracle SW	N/A	3 (Pilot subject omitted)	6
Tucson, AZ	CTL	Speedway and Wilmot NW	N/A	3 (Pilot subject omitted)	6
Tucson, AZ	CTL	Tanque Verde and Sabino Canyon NE	N/A	3 (Pilot subject omitted)	6
Ann Arbor, MI	RBT	Ellsworth and State	W Entry	4	8
Ann Arbor, MI	RBT	Ellsworth and State	W Exit	4	8
Ann Arbor, MI	RBT	Nixon and Huron	S Entry	4	8
Ann Arbor, MI	RBT	Nixon and Huron	S Exit	4	7
Cary, NC	RBT	Old Apex and Chatham	W Entry	5	10
Cary, NC	RBT	Old Apex and Chatham	W Exit	5	10
Columbus-Hilliard, OH	RBT	Cemetery and Main	N Entry	6	17
Columbus-Hilliard, OH	RBT	Cemetery and Main	S Entry	6	22
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Entry	6	10
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Exit	6	11
Oakland County, MI	RBT	Farmington and Maple	E Entry	4	8
Oakland County, MI	RBT	Farmington and Maple	E Exit	2	3
Oakland County, MI	RBT	Farmington and Maple	S Entry	5	9
Oakland County, MI	RBT	Farmington and Maple	S Exit	3	6

For wayfinding to the island, initial alignment had the highest error rates across all roundabout sites and all channelized turn lane sites. For roundabout sites, the initial alignment error rate was highest at the Cary, North Carolina location. For channelized turn lane sites, the initial alignment error rate was highest at the Greenbelt, Maryland location. Participants were more likely to miss the crosswalk, initially align outside the crosswalk, and end their crossing outside of the crosswalk at the channelized turn lane sites than the roundabout sites when wayfinding to the island. However, there were more interventions overall at the roundabout sites than the channelized turn lane sites, with the highest number of interventions occurring at the Hilliard, Ohio location (15 out of 39 total trials had at least one intervention).

7.3.2 Wayfinding on Island

Figures 7-4, 7-5, and 7-6 provide error rates for wayfinding on the island for all roundabout and channelized turn lane sites, and for roundabout and channelized turn lane sites by location. Table 7-3 provides detailed information on study locations and sample sizes for roundabout and channelized turn lane sites by intersection location.

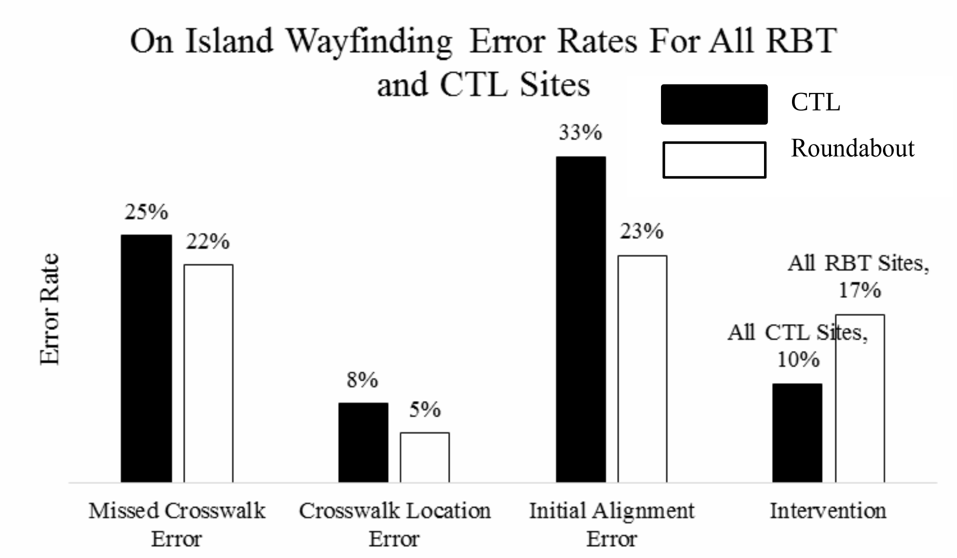


Figure 7-4: On Island Wayfinding Error Rates for All Roundabout and Channelized Turn Lane Sites

Bar graph shows the wayfinding error rates for crossings on the islands for all sites. 25% missed crosswalk error was recorded at CTL sites and 22% missed crosswalk error for roundabout sites. Crosswalk location errors were 8% for CTLs and 5% at roundabouts. The initial alignment errors for were 33% and 23% for CTLs and roundabouts, respectively. Interventions occurred on 10% of trials at CTLs and 17% of trials at roundabouts.

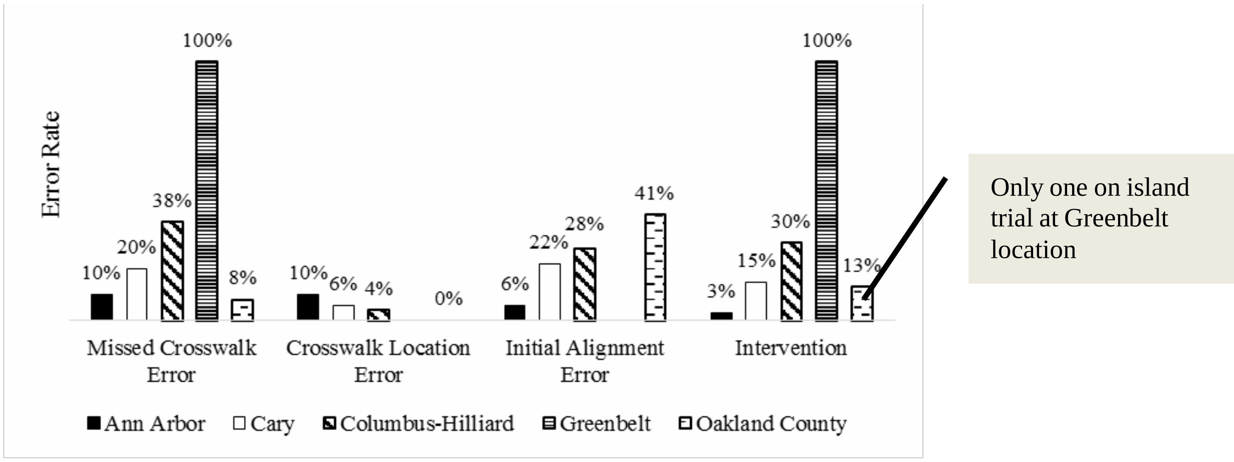


Figure 7-5: On Island Wayfinding Error Rates for Roundabout Sites

Bar graph shows the wayfinding error rates on islands for each of the roundabout sites. Note states "Only one on island trial at Greenbelt location." For missed crosswalk, there was 10% error rate at Ann Arbor, 20% at Cary, 38% at Columbus-Hilliard, 100% at Greenbelt and 8% at Oakland County. Crosswalk location errors were 10% at Ann Arbor and 6% at Cary, 4% at Columbus-Hilliard, 0% at Oakland County and not recorded at Greenbelt. The initial alignment error was 6% at Ann Arbor 22% at Cary, 28% at Columbus-Hilliard, no trial at Greenbelt, and 41% at Oakland County. Interventions occurred on 3% of trials at Ann Arbor, 15% of trials at Cary, 30% of trials at Columbus-Hilliard, 100% of trials at Greenbelt and 13% of trials at Oakland County.

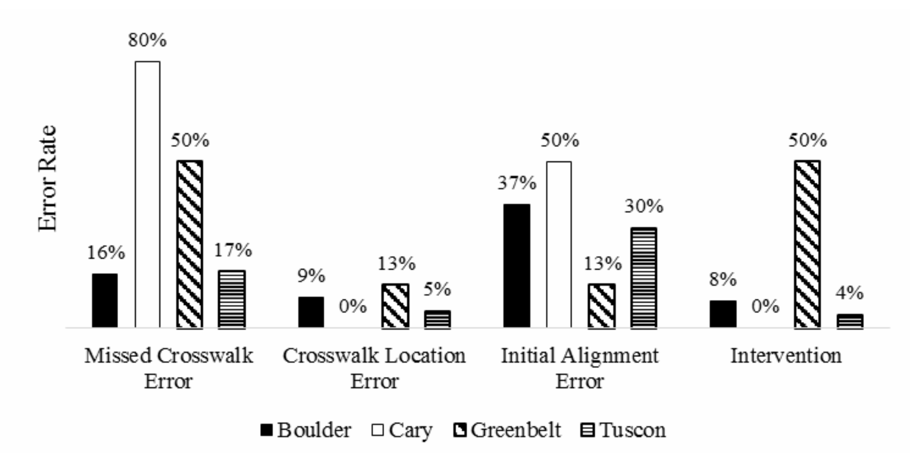


Figure 7-6: On Island Wayfinding Error Rates for Channelized Turn Lane Sites

Bar graph shows the wayfinding error rates for each of the CTL sites. For missed crosswalk, there was 16% error rate in Boulder, 80% at Cary site, 50% at Greenbelt, and 17% in Tucson. Crosswalk location errors were 9% at Boulder and 0% at Cary, 13% at Greenbelt and 5% in Tucson. The initial alignment errors were 37% at Boulder, 50% at Cary, 13% at Greenbelt and 30% at Tucson. Interventions occurred on 8% of trials at Boulder, 0% of trials at Cary, 50% of trials at Greenbelt and 4% of trials in Tucson.

Table 7-3: On Island Wayfinding Locations and Sample Sizes

Site Name	Site Type	Intersection	Approach	Number of Subjects	Number of Observations
Boulder, CO	CTL	Arapahoe and Foothills SW	NA	5	10
Boulder, CO	CTL	Foothills and Baseline NE	NA	5	10
Boulder, CO	CTL	Foothills and Baseline SW	NA	5	10
Boulder, CO	CTL	Canyon and 28th SW	NA	5	10
Boulder, CO	CTL	Pearl and 28th NE	NA	6	12
Boulder, CO	CTL	Pearl and 28th NW	NA	5	10
Cary, NC	CTL	Kildaire Farm and Tryon W	NA	5	10
Greenbelt, MD	CTL	Kenilworth and West NW	NA	6	10
Tucson, AZ	CTL	Grant and Oracle NE	NA	3 (Pilot subject omitted)	6
Tucson, AZ	CTL	Grant and Oracle SW	NA	3 (Pilot subject omitted)	6
Tucson, AZ	CTL	Speedway and Wilmot NW	NA	3 (Pilot subject omitted)	6
Tucson, AZ	CTL	Tanque Verde and Sabino Canyon NE	NA	3 (Pilot subject omitted)	6
Ann Arbor, MI	RBT	Ellsworth and State	W Entry	4	8
Ann Arbor, MI	RBT	Ellsworth and State	W Exit	4	8
Ann Arbor, MI	RBT	Nixon and Huron	S Entry	4	7
Ann Arbor, MI	RBT	Nixon and Huron	S Exit	4	6
Cary, NC	RBT	Old Apex and Chatham	W Entry	5	10
Cary, NC	RBT	Old Apex and Chatham	W Exit	5	10
Columbus-Hilliard, OH	RBT	Cemetery and Main	N Entry	6	15
Columbus-Hilliard, OH	RBT	Cemetery and Main	S Entry	6	22
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Entry	No Data	No Data
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Exit	1	1
Oakland County, MI	RBT	Farmington and Maple	E Entry	4	7
Oakland County, MI	RBT	Farmington and Maple	E Exit	2	3
Oakland County, MI	RBT	Farmington and Maple	S Entry	5	9
Oakland County, MI	RBT	Farmington and Maple	S Exit	3	5

Error rate findings for wayfinding on the island are similar to error rate findings for wayfinding to the island. For wayfinding on the island, initial alignment had the highest error rates across all roundabout sites and all channelized turn lane sites. For roundabout sites, the initial alignment error rate was highest at the Oakland County, Michigan location. For channelized turn lane sites, the initial alignment error rate was highest at the Cary, North Carolina location. On the island, participants were more likely to miss the crosswalk at the channelized turn lane sites than the roundabout sites. This is in stark contrast to our finding that when traveling to the island, CTL crosswalks were likely to be located (see Figure 7-1 and Table 7-5). There were more interventions overall at the roundabout sites than the channelized turn lane sites, with the highest number of interventions occurring at the Columbus-Hilliard, Ohio location (11 out of 37 total trials had at least one intervention). The 100% intervention rate at the Greenbelt, Maryland location is not reliable, since only one trial was recorded for wayfinding on the island, and this trial had an intervention.

7.3.3 Error Rates for Each Intersection Location

More detailed information on error rates for each intersection location is provided in Tables 7-4, 7-5, 7-6, and 7-7. Details for error criterion 1 (Missed Crosswalk Error), criterion 3 (Initial Alignment Error), and criterion 5 (Crossing Ending Location Error) are provided for trials to the island, and details for error criterion 1 (Missed Crosswalk Error) and criterion 3 (Initial Alignment Error) are provided for trials on the island. It should be noted that the crossing cues were not consistent even for two crossings at the same intersection, so the data is recorded for each approach or crosswalk.

Table 7-4: To Island Error Rates for Criterion 1, 3, and 5 at Roundabout Sites

Site Name	Site Type	Intersection	Approach	Missed Crosswalk Success	Missed Crosswalk Failure	Missed Crosswalk % Failure	Initial Alignment Success	Initial Alignment Failure	Initial Alignment % Failure	Crossing Ending Location Success	Crossing Ending Location Failure	Crossing Ending Location % Failure
Ann Arbor, MI	RBT	Ellsworth and State	W Entry	7	1	13%	7	1	13%	7	1	13%
Ann Arbor, MI	RBT	Ellsworth and State	W Exit	8	0	0%	6	2	25%	8	0	0%
Ann Arbor, MI	RBT	Nixon and Huron	S Entry	8	0	0%	8	0	0%	8	0	0%
Ann Arbor, MI	RBT	Nixon and Huron	S Exit	6	1	14%	7	0	0%	7	0	0%
Cary, NC	RBT	Old Apex and Chatham	W Entry	8	2	20%	3	7	70%	10	0	0%
Cary, NC	RBT	Old Apex and Chatham	W Exit	9	1	10%	6	4	40%	9	1	10%
Columbus-Hilliard, OH	RBT	Cemetery and Main	N Entry	9	8	47%	5	8	62%	4	4	50%
Columbus-Hilliard, OH	RBT	Cemetery and Main	S Entry	15	7	32%	18	4	18%	14	4	22%
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Entry	7	3	30%	6	3	33%	7	2	22%
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Exit	10	1	9%	6	5	45%	4	7	64%
Oakland County, MI	RBT	Farmington and Maple	E Entry	2	6	75%	4	4	50%	7	1	13%
Oakland County, MI	RBT	Farmington and Maple	E Exit	2	1	33%	3	0	0%	2	1	33%
Oakland County, MI	RBT	Farmington and Maple	S Entry	7	2	22%	7	2	22%	8	1	11%
Oakland County, MI	RBT	Farmington and Maple	S Exit	5	1	17%	1	5	83%	4	2	33%

Table 7-5: To Island Error Rates for Criterion 1, 3, and 5 at Channelized Turn Lane Sites

Site Name	Site Type	Intersection	Missed Crosswalk Success	Missed Crosswalk Failure	Missed Crosswalk % Failure	Initial Alignment Success	Initial Alignment Failure	Initial Alignment % Failure	Crossing Ending Location Success	Crossing Ending Location Failure	Crossing Ending Location % Failure
Boulder, CO	CTL	Arapahoe and Foothills SW	9	1	10%	10	0	0%	5	4	44%
Boulder, CO	CTL	Foothills and Baseline NE	10	0	0%	6	4	40%	4	6	60%
Boulder, CO	CTL	Foothills and Baseline SW	10	0	0%	1	9	90%	3	7	70%
Boulder, CO	CTL	Canyon and 28th SW	10	0	0%	7	3	30%	8	2	20%
Boulder, CO	CTL	Pearl and 28th NE	12	0	0%	6	6	50%	8	3	27%
Boulder, CO	CTL	Pearl and 28th NW	10	0	0%	6	4	40%	7	2	22%
Cary, NC	CTL	Kildaire Farm and Tryon W	8	2	20%	4	6	60%	8	2	20%
Greenbelt, MD	CTL	Kenilworth and West NW	9	1	10%	3	7	70%	3	7	70%
Tucson, AZ	CTL	Grant and Oracle NE	6	0	0%	5	1	17%	5	1	17%
Tucson, AZ	CTL	Grant and Oracle SW	6	0	0%	5	1	17%	4	2	33%
Tucson, AZ	CTL	Speedway and Wilmot NW	6	0	0%	4	2	33%	4	2	33%
Tucson, AZ	CTL	Tanque Verde and Sabino Canyon NE	6	0	0%	4	2	33%	5	1	17%

Table 7-6: On Island Error Rates for Criterion 1 and 3 at Roundabout Sites

Site Name	Site Type	Intersection	Approach	Missed Crosswalk Success	Missed Crosswalk Failure	Missed Crosswalk % Failure	Initial Alignment Success	Initial Alignment Failure	Initial Alignment % Failure
Ann Arbor, MI	RBT	Ellsworth and State	W Entry	6	2	25%	6	0	0
Ann Arbor, MI	RBT	Ellsworth and State	W Exit	7	1	13%	6	1	14%
Ann Arbor, MI	RBT	Nixon and Huron	S Entry	7	0	0%	7	0	0%
Ann Arbor, MI	RBT	Nixon and Huron	S Exit	6	0	0%	6	0	0%
Cary, NC	RBT	Old Apex and Chatham	W Entry	8	2	20%	7	2	22%
Cary, NC	RBT	Old Apex and Chatham	W Exit	8	2	20%	7	2	22%
Columbus-Hilliard, OH	RBT	Cemetery and Main	N Entry	6	9	60%	7	0	0%
Columbus-Hilliard, OH	RBT	Cemetery and Main	S Entry	17	5	23%	12	8	40%
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Entry	No Data	No Data	No Data	No Data	No Data	No Data
Greenbelt, MD	RBT	Cherrywood and Greenbelt Metro	W Exit	0	1	100%	No Data	No Data	No Data
Oakland County, MI	RBT	Farmington and Maple	E Entry	6	1	14%	2	4	67%
Oakland County, MI	RBT	Farmington and Maple	E Exit	3	0	0%	2	1	33%
Oakland County, MI	RBT	Farmington and Maple	S Entry	8	1	11%	8	0	0%
Oakland County, MI	RBT	Farmington and Maple	S Exit	5	0	0%	1	4	80%

Table 7-7: On Island Error Rates for Criterion 1 and 3 at Channelized Turn Lane Sites

Site Name	Site Type	Intersection	Missed Crosswalk Success	Missed Crosswalk Failure	Missed Crosswalk % Failure	Initial Alignment Success	Initial Alignment Failure	Initial Alignment % Failure
Boulder, CO	CTL	Arapahoe and Foothills SW	9	1	10%	9	0	0%
Boulder, CO	CTL	Foothills and Baseline NE	7	3	30%	1	8	89%
Boulder, CO	CTL	Foothills and Baseline SW	9	1	10%	5	4	44%
Boulder, CO	CTL	Canyon and 28th SW	10	0	0%	7	3	30%
Boulder, CO	CTL	Pearl and 28th NE	10	2	17%	7	3	30%
Boulder, CO	CTL	Pearl and 28th NW	7	3	30%	5	2	29%
Cary, NC	CTL	Kildaire Farm and Tryon W	2	8	80%	1	1	50%
Greenbelt, MD	CTL	Kenilworth and West NW	5	5	50%	7	1	13%
Tucson, AZ	CTL	Grant and Oracle NE	6	0	0%	5	1	17%
Tucson, AZ	CTL	Grant and Oracle SW	5	1	17%	2	3	60%
Tucson, AZ	CTL	Speedway and Wilmot NW	4	2	33%	3	1	25%
Tucson, AZ	CTL	Tanque Verde and Sabino Canyon NE	5	1	17%	4	1	20%

8 APPENDIX B: YIELD MODEL DETAILS

This appendix summarizes the yield modeling results for the combined data for TOPR-34 and NCHRP 3-78b. In order to create models to predict driver yielding rates for blind and sighted pedestrians, Stata was used to analyze data collected at two-lane roundabouts in Ohio, Maryland, Michigan, North Carolina, Washington, Oregon, Indiana, Wisconsin, and New York.

8.1 Introduction

A contributing factor to the accessibility concerns of many multi-lane roundabouts is believed to be the low yielding rates at these sites. Yielding rate is one of the critical performance measures for accessibility identified by members of this team in NCHRP Report 674 (Schroeder et al., 2011). There is strong evidence from research that RRFBs increase yielding at single-lane roundabouts, but it is unclear if a similar increase in yielding would be seen at multi-lane roundabouts. This question is explored in this task through empirical research at various two-lane roundabouts with and without RRFBs in the United States. In addition, the effect of geometric variables, such as fastest path radius, and behavioral variables, such as average vehicle speed at crosswalk, on yielding will also be investigated. This study seeks to better understand driver yielding behavior and what behavioral and site attributes affect driver yielding probability.

8.2 Methodology

8.2.1 Data Collection

A naturalistic yielding study was performed to determine the driver yielding rate using randomly generated pedestrian events at the crosswalk with and without the use of a long white cane. Because the analysis focuses on the probability of yielding, the research team derived the dependent variable, yielding rate, from observed active yields at each site. Active yields are defined as those events where the motorist slowed or stopped for a crossing pedestrian or a pedestrian waiting on the curb to cross and the pedestrian was the only reason the motorist stopped or slowed. Yield probability is calculated by dividing the total number of active yields by the sum of active yields and no yields.

$$Yield\ Probability\ =\ \frac{\#\ of\ Active\ Yields}{Sum\ of\ Active\ Yields\ and\ No\ Yields}$$

The research team did not consider passive yields, or those events where the motorist yielded to the pedestrian, but was already stopped for another reason, since passive yields are typically primarily a function of traffic volume and not related to geometric factors. Data collection was planned for periods during which the occurrence of passive yields was limited (times without excessive congestion).

In the experiment, the pedestrian waited at the edge of the curb facing the direction of travel across the crosswalk with their head turned toward oncoming traffic to indicate their intention to make the crossing. The pedestrian accepted (completed the crossing from the curb to the splitter island) a yield or a gap. Vehicles in both lanes in the direction of interest were considered when classifying driver behavior. To avoid confusing drivers and the collection of inaccurate data, the pedestrian continued to walk beyond the end of the crosswalk before beginning another trial.

To avoid any unusual reactions by motorists, the pedestrian wore no unusually bright or distracting attire. Trials were performed at the entry or exit leg in a randomized order. Approximately half of the trials employed the use of a long white cane, to simulate the arrival of a blind pedestrian. In all of the trials, the pedestrian took one step "into" the crosswalk in accordance with most states' yielding laws. Variables collected are shown in Table 9-1.

Table 8-1: Variables of Interest in Yielding Study

Factor		Description	Value
Independent Variables	EXT	Exit or entry approach of roundabout	Exit=1, Entry=0
	RDS	Fastest path radius of roundabout in feet	Continuous variable
	XSPD_AVE	Average vehicle speed at crosswalk in mph	Continuous variable
	RRFB	Presence of RRFB at crosswalk	Yes=1, No=0
	SIGHT_D	Pedestrian crossing sight distance	Not provided=1, Provided=0
	OL_DEC	Overlapping driver decision points	1=Present, 0=Not Present
Dependent Variable	YIELDR	Yielding rate for all subjects	Continuous variable

8.2.2 Modeling Approach

Stata was used to analyze the data collected in order to create a model to predict the probability of a driver yielding to a pedestrian or pedestrians on a crossing event. In preparation for modeling, observations were removed if yielding information was missing. Sites with one or three lanes at the crosswalk and sites with slip lanes were not included in this analysis. The sample sizes for each state and overall are provided in Table 8-2, and a table with detailed site information can be found in Appendix A. Each observation represents one site for each state with a yielding rate derived from no less than 15 trial crossings (Max=27; Min=15; Average=21) at the site. The results of a Student T-Test for Independent Means (T-value=0.590; *p*-value=0.557) indicate no significant difference between yielding rates for "blind" pedestrians and yielding rates for "sighted" pedestrians, so the yielding rates were combined as the response variable, YIELDR.

Table 8-2: Sample Sizes by State

State	# of Observations (With Cane-"Blind")	# of Observations (Without Cane-"Sighted")	Total # of Observations for Study
Ohio	3	3	6
Maryland	1	1	2
Michigan	3	3	6
North Carolina	4	4	8
Washington	5	5	10
Oregon	4	4	8
Indiana	2	2	4
Wisconsin	2	3	5
New York	3	3	6
TOTAL	**27**	**28**	**55**

In the first step of modeling, a correlation table was created to determine if any variables are significantly related to each other, or intercorrelated. In the next step, multivariable linear regression models were generated to predict the driver yielding rates, taking into account macroscopic site conditions. Predicted yielding rates were produced based on two variable selection processes:

- Full Model – uses all independent variables regardless of *p*-value.
- Manual Selection – a custom model that is informed by the first modeling result and examination of correlation and collinearity, and considers practical significance and feasibility of implementing variables in simulation rather than focusing on statistical fit.

8.3 Results

8.3.1 Descriptive Statistics

Data analysis began with finding the mean, standard deviation, maximum, and minimum for all variables used in the modeling process. The descriptive statistics help characterize the geometric and treatment features at each study site based on the data collected, and offer a better understanding of data trends and variability. Values are provided in relation to the dependent variable of interest, YIELDR. The average yielding rate for "blind" pedestrians was 72.3% while the average yielding rate for "sighted" pedestrians was 67.5%. The average yielding rate for all pedestrians was 69.9%. The average speed at crosswalk for the sites was 21 mph.

Data showed that half the sites were located at roundabout exits. Over 70% (18) of the sites featured RRFBs, while three sites (11%) featured raised crosswalks and two sites (7%) featured sound strips or rumble strips. Raised crosswalks, sound strips, and rumble strips were not included as explanatory variables in the analysis due to the small sample size. Further descriptive statistics are provided below.

Table 8-3: Descriptive Statistics for Roundabout Sites

		All Data			
Variable	**N**	**Mean**	**StdDev**	**Max**	**Min**
Dependent Variables					
YIELDR	55	69.9	29.5	100	0
Independent Variables					
EXT	55	0.49	0.50	1	0
RDS	55	311	280	1000	73
XSPD_AVE	55	20.9	3.7	29	13
RRFB	55	0.64	0.5	1	0
SIGHT_D	55	0.33	0.47	1	0
OL_DEC	55	0.42	0.50	1	0

8.3.2 Correlation

A summarized version of the Pearson correlation table showing the correlation between the yielding rate for all pedestrians and the explanatory variables is shown in Table 8-4. Correlation coefficients are provided with the significance level indicated by superscripted asterisks.

The following variables show a significant negative or inverse correlation with the YIELDR variable, suggesting a decrease in yielding with an increase in the variable (or binary variable change from 0 to 1): EXT, RDS, XSPD_AVE, SIGHT_D, and OL_DEC. No significant correlation was found between RRFB and the dependent variable. Several of the independent variables are intercorrelated, which affects their suitability to be included in the same models due to multicollinearity. These intercorrelations will be addressed in the recommended models section to follow.

Table 8-4: Correlation Table for Roundabout Sites

	n=55	YIELDR	EXT	RDS	XSPD_AVE	RRFB	SIGHT_D	OL_DEC
Pearson Correlation	YIELDR	1.0000						
	EXT	-0.2494*	1.0000					
	RDS	-0.5949*	0.5826*	1.0000				
	XSPD_AVE	-0.3863*	0.6974*	0.7017*	1.0000			
	RRFB	0.1191	-0.0137	0.1252	-0.0187	1.0000		
	SIGHT_D	-0.3639*	0.4002*	0.5098*	0.5235*	0.0439	1.0000	
	OL_DEC	-0.2494**	0.1997	0.4232*	0.2718*	0.1811	0.1943	1.0000

*$p<0.05$, **$p<0.10$

8.4 Model Development

The yielding rate is a continuous variable that is constrained to be between 0% and 100%, making it suitable for use in multivariable linear regression modeling. Regression diagnostics were applied to the dependent and explanatory variables to verify that the data met the assumptions of linear regression. The form of the multivariable linear regression model for yielding rate is:

$$Y=a + b_1X_1 + b_2X_2 + b_3X_{3\,(\ldots)}$$

Where:

Y is the value of the dependent variable, what is being predicted or explained;

a is the constant or intercept;

b_1 is the slope for X_1, the first independent variable that is explaining the variance in Y;

b_2 is the slope for X_2, the second independent variable that is explaining the variance in Y;

b_3 is the slope for X_3, the third independent variable that is explaining the variance in Y; and

b_4 and onwards are the slopes for additional independent variables that explain the variance in Y.

Based on this equation, if the values of all variables except one independent variable (X_i) are kept constant, one unit increase in the value of X_i will increase the value of the response variable Y by the slope of X_i. The R^2 statistic is generally used in regression models to describe how much variability of the data is explained by the model. For multivariable linear regression models, the variability of the model can be evaluated by the adjusted R^2 statistic, which is an adjustment of the R^2 based on the number of observations and predictors in the model. Higher adjusted R^2 is an indicator of a better fit of the model to the data and the proportion of the data that can be explained by the model.

Final models were developed using a manual selection process informed by the results of modeling with all independent variables regardless of *p*-value, as well as the results of the correlation analysis. Significantly associated independent variables were not included in the same model. Two models were investigated to predict driver yielding behavior: 1) a geometric model including explanatory variables for approach, fastest path radius, treatment, pedestrian sight distance, and overlapping decision points, and 2) a behavioral model including explanatory variables for approach, average vehicle speed at crosswalk, and treatment.

The full multivariable linear regression model results for each dependent variable are shown in Table 5. The parameter significance level is indicated by superscripted asterisks. Table 8-5 shows that factor RDS is significant to the model with *p*-value<0.05, and factor RRFB is significant to the model with *p*-value<0.10. The adjusted R^2 value is 0.34.

Table 8-5: Full Model to Predict Yielding Rates to "Blind" and "Sighted" Pedestrians

	All Sites Regression Coefficient	Std Error	p	95% Conf Interval	
EXT	4.652	9.218	0.616	-13.882	23.186
RDS	-0.070	0.018	0.000*	-0.107	-0.033
XSPD_AVE	0.761	1.477	0.609	-2.209	3.730
RRFB	13.074	6.941	0.066**	-0.882	27.030
SIGHT_D	-6.815	8.344	0.418	-23.591	9.962
OL_DEC	-1.545	7.337	0.834	-16.298	13.207
Constant	68.111	27.016	0.015	13.792	122.430
Prob > F	0.000				
R^2	0.409				
Adj. R^2	0.335				

*p<0.05, **p<0.10

After generating the full model, the data were examined for strong correlations and significant linear relationships between the independent variables. Strong collinearity effects were additionally corroborated by performing VIF (variance inflation factor) tests in Stata. Any two explanatory variables that were found to be significantly linearly related were not included in the same final model, but were evaluated as controls in the model building process. Significant linear relationships and strong significant correlations were found between:

- RDS and EXT
- XSPD_AVE and EXT
- XSPD_AVE and RDS
- SIGHT_D and EXT
- SIGHT_D and RDS
- OL_DEC and RDS

Table 8-6 presents a summary of the model building process for the geometric model. The model with the highest adjusted R^2 value includes fastest path radius and RRFB as explanatory factors for driver yielding behavior. Controlling for approach, pedestrian sight distance, and overlapping decision points, the factors fastest path radius and RRFB remain significant to the model (p<0.10) and their effect on yielding remains nearly the same as in the model that includes only fastest path radius and RRFB as variables of interest. Because the effects of the significant factors remain nearly the same when controlling for additional explanatory variables, it is reasonable to recommend Model 2.

Table 8-6: Model Building Process for Geometric Yielding Model

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
RDS	-0.063*	-0.065*	-0.072*	-0.068*	-0.071*	-0.066*
RRFB		11.947**	12.508**	12.471**	12.689**	12.664**
EXT			6.132	6.977	6.056	6.901
SIGHT_D				-5.796		-5.825
OL_DEC					-1.410	-1.502
Constant	89.331	82.535	81.207	81.432	81.376	81.613

R^2	0.354	0.392	0.399	0.406	0.400	0.406
Adj. R^2	0.342	0.369	0.364	0.358	0.352	0.345

**p*<0.05, ***p*<0.10

Table 8-7 presents a model for predicting driver yielding behavior based on geometric features of the roundabouts under study. The recommended geometric model estimates an 11.9% increase in the yielding rate in the presence of RRFB, and a 0.07% decrease in the yielding rate for every one foot increase in the fastest path radius.

Table 8-7: Recommended Geometric Model to Predict Yielding Rates to "Blind" and "Sighted" Pedestrians

	YIELDR Regression Coefficient	Std Error	p	95% Conf Interval	
RDS	-0.065	0.011	0.000*	-0.088	-0.042
RRFB	11.947	6.619	0.077**	-1.335	25.229
Constant	82.535	6.057	0.000	70.380	94.690
Prob > F	0.000				
R^2	0.392				
Adj. R^2	0.369				

**p*<0.05, ***p*<0.10

Table 8-8 presents a summary of the model building process for the behavioral model. The model with the highest adjusted R^2 value includes average speed at crosswalk in mph as an explanatory factor for driver yielding behavior. Controlling for approach and RRFB, average speed at crosswalk in mph remains significant to the model ($p<0.05$) with the same effect on yielding. Because average speed at crosswalk in mph is collinear with and acts as a proxy for approach, it is reasonable to recommend Model 2 for predicting driver yielding behavior based on driver behavior and the presence of treatments at the roundabouts under study. Table 8-9 presents a centered version of Model 2 using the average speed at crosswalk in mph and RRFB as predictors for yielding. Average speed at crosswalk in mph was centered to its mean (21 mph), which involved subtracting the mean from and dividing by the standard deviation (3.647) for each yielding value. Centering to the mean makes it simpler to interpret the constant, but gives the same result for predicting yielding by speed as the uncentered model. For the centered model, the mean yielding rate is 64% for the mean average speed at crosswalk, 21 mph. For every one mile per hour increase in the mean average speed at crosswalk, the yielding rate is estimated to decrease by approximately 12.0%. The model also estimates an 8.1% increase in the yielding rate in the presence of RRFB.

Table 8-8: Model Building Process for Behavioral Yielding Model

	Model 1	Model 2	Model 3
XSPD_AVE	-3.071*	-3.055*	2.778**
RRFB		6.799	6.797
EXT			-2.919
Constant	134.077	129.402	125.046
R^2	0.149	0.162	0.163
Adj. R^2	0.133	0.130	0.114

**p*<0.05, ***p*<0.10

Table 8-9: Recommended Behavioral Model to Predict Yielding Rates to "Blind" and "Sighted" Pedestrians

	YIELDR				
	Regression Coefficient	Std Error	p	95% Conf Interval	
centeredXSPD_AVE	-11.996	3.518	0.001	-19.055	-4.937
RRFB	8.093	7.563	0.290	-7.084	23.270
Constant	64.050	6.040	0.000	51.929	76.171
Prob > F	0.004				
R^2	0.194				
Adj. R^2	0.163				

**p*<0.05, ***p*<0.10

8.5 Summary

Multivariable linear regression models were generated to predict driver yielding rates to "blind" and "sighted" pedestrians at two-lane roundabouts in nine states in the United States. Since no significant difference was found between yielding rates to "blind" and "sighted" pedestrians, final models were created through manual selection informed by full modeling efforts and correlation analysis using the dependent variable of interest, driver yielding rate to all pedestrians (YIELDR). Separate models were created focusing on geometric and behavioral predictors for driver yielding behavior. Fastest path radius (RDS), presence of RRFB (RRFB), and average vehicle speed at crosswalk (XSPD_AVE) were found, in their respective models, to be significant explanatory factors for driver yielding to pedestrians at the two-lane roundabout sites. The recommended geometric model estimates an 11.9% increase in the yielding rate in the presence of RRFB, and a 0.07% decrease in the yielding rate for every one foot increase in the fastest path radius. The recommended behavioral model estimates an 8.1% increase in the yielding rate in the presence of RRFB, and estimates the yielding rate to decrease by approximately 12.0% for every one mile per hour increase in the mean average speed at crosswalk (21 mph).

Table 8-10: Detailed Site Information for Yield Models

#	State	City	Intersection Name	Approach	Location
1	OH	Hilliard	Cemetery/Main	East	Entry
2	OH	Hilliard	Cemetery/Main	East	Exit
3	OH	Hilliard	Cemetery/Main	West	Exit
4	MD	Greenbelt	Cherrywood/Metro	West	Entry
5	MI	Ann Arbor	Ellsworth/State	West	Entry
6	MI	Ann Arbor	Ellsworth/State	West	Exit
7	MI	Novi	Maple/Farmington	South	Entry
8	MI	Novi	Maple /Farmington	North	Exit
9	NC	Davidson	Davidson Gateway-Harbour Place/Griffith	East	Entry
10	NC	Davidson	Davidson Gateway-Harbour Place/Griffith	East	Exit
11	NC	Davidson	Davidson Gateway-Harbour Place/Griffith	West	Entry

12	NC	Davidson	Davidson Gateway-Harbour Place/Griffith	West	Exit
13	WA	Olympia	4th/Olympic	East	Entry
14	WA	Olympia	4th/Olympic	North	Entry
15	WA	Olympia	4th/Olympic	North	Exit
16	WA	Olympia	14th/Jefferson	East	Entry
17	WA	Olympia	14th/Jefferson	East	Exit
18	OR	Springfield	Pioneer/Hayden Bridge	East	Entry
19	OR	Springfield	Pioneer/Hayden Bridge	East	Exit
20	OR	Springfield	Pioneer/Hayden Bridge	South	Entry
21	OR	Springfield	Pioneer/Hayden Bridge	South	Exit
22	IN	Carmel	Clay Terrace/Clay Terrace	North	Entry
23	IN	Carmel	Clay Terrace/Clay Terrace	North	Exit
24	WI	Oshkosh	Jackson/Murdock	South	Entry
25	WI	Oshkosh	Jackson/Murdock	South	Exit
26	WI	Oshkosh	Jackson/Murdock	East	Entry
27	WI	Oshkosh	Jackson/Murdock	East	Exit
28	NY	Albany	Fuller/Washington	North	Exit
29	NY	Albany	Fuller/Washington	South	Entry
30	NY	Albany	Fuller/Washington	South	Exit

9 APPENDIX C: RISK MODEL DETAILS

This appendix summarizes the risk modeling results for the combined data for TOPR-34 and NCHRP 3-78b. In order to create models to predict pedestrian risk rate, Stata was used to analyze data collected at roundabouts in states of Washington, Oregon, New York, Michigan, North Carolina, Maryland, Ohio, Wisconsin, and channelized turn lane locations in Colorado, North Carolina, Maryland and Arizona.

9.1 Methodology

9.1.1 Definition of Risk Models & Data Collection

As part of accessibility audits of the intersections for the purpose of NCHRP 3-78b project and the FHWA TOPR34 project, the research team recruited blind subjects to participate in an indicator study which asked them to approach and stand at the crosswalk location at curb and identify when they would cross by raising their hand. During the study subjects were accompanied at all times by an orientation and mobility (O&M) specialist. After participant's indication, the O&M specialist would rank the participant's decision as estimated intervention, risky event, or safe event as described below:

1. Estimated Intervention – if the pedestrian had stepped into the roadway at the time the decision was made, the O&M specialist would have chosen to intervene by physically restraining the participant to avoid a collision with an approaching vehicle.
2. Risky Event – if the pedestrian had stepped into the roadway at the time the decision was made, the O&M specialist may have chosen to intervene, depending on driver reaction, pedestrian walking speed, or other considerations.
3. Safe Event – if the pedestrian had stepped into the roadway at the time the decision was made, the O&M specialist would not have chosen to intervene, and would have let the crossing proceed.

Each subject completed approximately ten trials at each study location and 5 to 7 subjects were recruited for each location. Based on the count of trials that were ranked as estimated intervention or risky event, the terms intervention rates and intervention-risky rates were defined for each site as below:

$$Intervention\ Rate = \frac{Count\ of\ All\ Intervention\ Events\ Across\ All\ Subjects\ for\ One\ site}{Count\ of\ All\ Trials\ Across\ All\ Subjects\ for\ One\ site}$$

$$Intervention - Risky\ Rate = \frac{Count\ of\ All\ Intervention\ \text{plus Risky}\ Events\ Across\ All\ Subjects\ for\ One\ site}{Count\ of\ All\ Trials\ Across\ All\ Subjects\ for\ One\ site}$$

In order to predict the rate of intervention and intervention-risky events, the research team collected many other performance measures that they hypothesized might contribute to higher risky and intervention situations for bind pedestrians. These variables are results of many hours of research study and observation of blind pedestrian crossing, and interviews with blind pedestrians. The variables are defined in Table 9-1.

Table 9-1: Variables of Interest in Risk Modeling

Variable	Description	Value
CTL	Channelized Turn Lane	Channelized Turn Lane=1, otherwise=0
RBTN	Roundabout entry	Roundabout entry=1, otherwise=0
RBTX	Roundabout exit	Roundabout exit =1, otherwise=0
NOISE	Noise level experienced at the study location	High=1, Low=0
SIGHT_D	Whether the pedestrian sight distance was provided or not	Sight distance provide=1, otherwise=0
LU	Lane Utilization	Unbalanced=1, balanced=0,
OL_DEC	Overlapping decision Points between yielding to pedestrian and finding gap in cross traffic	Two decisions overlap=1, otherwise=0
XSPED_AVE	Average pedestrian speed at crosswalk (>= 10mph)	Continuous variable
N2	Number of lanes	Single lane =0, more than one lane=1
YR	Average driver yield rate to pedestrians	Continuous variable
YUR	Average yield utilization rate by blind pedestrians	Continuous variable
RDS	Approach fastest path radius	Continuous variable
INT	Intervention rates	Continuous variable
INTR	Total of intervention and risky events rate	Continuous variable

Stata was used to analyze the data collected in order to create a model to predict the likelihood of intervention or intervention-risky crossings at an intersection by a blind pedestrian. Since the dependent variables are continuous and the independent variables are a combination of binary and continuous variables, multivariable linear regression models were generated.

9.2 Results

9.2.1 Descriptive Statistics

The descriptive statistics for the variables are shown in Table 9-2. In total, 52 observations are gathered and included in the dataset, 40 roundabouts locations (entry and exit) and 12 channelized turn lane locations.

Table 9-2 Descriptive Statistics for Risk Modeling Variables

Variables		N	Ave	St. Dev	Min	Max
Dependent Variables	**INT**	52	0.048	0.052	0	0.217
	INTR	52	0.170	0.126	0	0.6
Binary Independent Variables	**CTL**	52	0.231	0.425	0	1
	RBTN	52	0.385	0.491	0	1
	RBTX	52	0.385	0.491	0	1
	NOISE	52	0.308	0.466	0	1
	SIGHT_D	52	0.327	0.474	0	1
	LU	52	0.212	0.412	0	1
	PL_DEC	52	0.423	0.499	0	1
	N2	52	0.635	0.486	0	1
Continues Independent variables	**XSPD_AVE**	52	19.38	4.92	0	30.5
	YR	52	0.59	0.29	0	1
	YUR	52	0.623	0.246	0.14	1
	RDS	52	241	216	50	1000

Across the study locations, the data shows that the average intervention rate is 0.05 and the average intervention-risky rate is 0.17. This suggests that, on average, blind participants made “bad” crossing decisions which may have resulted in an intervention about 5% of the time. The chance that a blind participant would make either a risky or dangerous (intervention) crossing decision at an intersection is about 17% among all locations. The results show that 31% of the study locations are associated with high noise levels (NOISE=0.308). Also, 33% of the locations were associated with not providing enough pedestrian sight distance (SIGHT_D = 0.327). On average, 21% of the multi-lane roundabouts suffer from imbalanced lane utilization either at entry or exit. Forty-two percent of the crosswalks are located at the point where drivers would be likely to be also looking for a gap in crossing traffic and, therefore, the locations have overlapping decision points. The average speed across all crossings observed at the crosswalk locations was 19 mph and the average observed yielding rate to pedestrians (blind and sighted), across all crossings was 59%.

9.2.2 Correlation

A summarized version of the Pearson correlation table showing the correlation between the intervention rate and intervention-risky rate for all sites and the explanatory variables is shown in Table 9-3. Correlation coefficients are provided with the significance level indicated by superscripted asterisks. Since RBTN, RBTX, and CTL all together represent the whole sample size and CTL can be described as the combination of RBTN and RBTX, the variable CTL was eliminated from the rest of the analysis.

The following variables show a significant positive correlation ($p<0.01$) with dependent variable INT; NOISE, SIGHT_D, OL_DEC, XSPD_AVE, RDS, RBTN. The variable N2, RBTX and YR show a significant ($p<0.05$, and $p< 0.1$ respectively) negative correlation with dependent variable INT.

The following variables show a significant positive correlation ($p<0.01$) with dependent variable INTR; NOISE, SIGHT_D, OL_DEC, XSPD_AVE, RDS. The variables RBTN and YR are positively correlated with $p<0.05$. No significant correlation was found for LU (lane utilization) and YUR (yield utilization rate) in relation to either INT or INTR and therefore these variables are eliminated from modeling considerations in the next steps.

Table 9-3 Correlation Table for Variables

n=52	INT	INTR	N2	NOISE	SIGHT_D	LU	OL_DEC	YR	XSPD_AVE	YUR	RDS	RBTN	RBTX
INT	1												
INTR	0.8142**	**1**											
N2	0.2082	0.2892*	**1**										
NOISE	0.6949**	0.5765**	0.1597	**1**									
SIGHT_D	0.4294**	0.4088**	0.018	0.3348**	**1**								
LU	-0.1908	-0.089	0.393**	-0.0392	-0.2606+	**1**							
OL_DEC	0.398**	0.3936**	0.0031	0.5255**	0.3989**	-0.0623	**1**						
YR	-0.2587+	-0.334*	0.2816*	-0.2609+	-0.2142	0.1128	-0.3305*	**1**					
XSPD_AVE	0.3975**	0.3628**	0.2257	0.3098*	0.1563	-0.2299	0.2516+	-0.3279*	**1**				
YUR	0.1374	0.0975	0.4474**	0.0478	-0.1702	-0.15	-0.1171	0.3911**	0.2816*	**1**			
RDS	0.4556**	0.4855**	0.3893**	0.4373**	0.1196	0.2063	0.251	-0.3067*	0.2892*	0.0344	**1**		
RBTN	0.4632**	0.3137*	0.3536*	0.415**	0.2074	-0.0223	0.1231	-0.2361	0.3522*	0.284*	0.4405**	**1**	
RBTX	-0.3148*	-0.149	0.2715+	-0.3558*	-0.3824**	0.268+	-0.277	0.4084**	-0.1822	0.2358	-0.2238	-0.63	**1**

**$p<0.005$, *$p<0.05$, +$p<0.10$

INT	Intervention rates
INTR	Total of intervention and risky events rate
N2	Number of lanes
NOISE	Noise level experienced at the study location
SIGHT_D	Whether the pedestrian sight distance was provided or not
LU	Lane Utilization
OL_DEC	Overlapping decision Points between yielding to pedestrian and finding gap in cross traffic
XSPED_AVE	Average pedestrian speed at crosswalk (>= 10mph)
YR	Average driver yield rate to pedestrians
YUR	Average yield utilization rate by blind pedestrians
RDS	Approach fastest path radius
RBTN	Roundabout entry
RBTX	Roundabout exit

The correlation table revealed significant intercorrelation between independent variables. For example, XSPD_AVE (speed) and RDS (radius) are strongly correlated, which is expected since geometric design of the roundabout or CTL (radius) is proven to be one of the factors that control speed. Therefore, RDS is also excluded from consideration for model development. The variables listed below have a significant intercorrelation with each other:

- NOISE: SIGHT_D, OL_DEC, YR, XSPD_AVE, RDS, RBTX, RBTN
- SIGHT_D: NOISE, LU, OL_DEC, RBTX, RBTN
- LU: SIGHT_D, RBTN
- OL_DEC: NOISE, SIGHT_D, YR, XSPD_AVE, RBTN
- YR: N2, NOISE, OL_DEC, XSPD_AVE, RDS, RBTX, RBTN
- XSPD_AVE: NOISE, OL_DEC, YR, RDS, RBTN, RBTX, YUR
- YUR: N2, YR, XSPD_AVE, RBTN
- RDS: N2, NOISE, XSP_AVE, YR
- RBTN: NOISE SIGHT_D, LU, OL_DEC, YR, YUR
- RBTX: N2, NOISE, XSPD_AVE, YUR, RDS

The significant intercorrelations between the independent variables were used as cues to manually select these variables for model development.

9.3 Model Development

Intervention and intervention-risky rates are continuous variables that are constrained to be between 0% and 100%, making them suitable for use in multivariable linear regression modeling. Regression diagnostics were applied to the dependent and explanatory variables to verify that the data met the assumptions of linear regression. The form of the multivariable linear regression model for yielding rate is:

$$Y=a + b_1X_1 + b_2X_2 + b_3X_{3\,(\ldots)}$$

Where:

Y is the value of the dependent variable, what is being predicted or explained;

a is the constant or intercept;

b_1 is the slope for X_1, the first independent variable that is explaining the variance in Y;

b_2 is the slope for X_2, the second independent variable that is explaining the variance in Y;

b_3 is the slope for X_3, the third independent variable that is explaining the variance in Y; and

b_4 and onwards are the slopes for additional independent variables that explain the variance in Y.

Based on this equation, if the values of all variables except one independent variable (X_i) are kept constant, one unit increase in the value of X_i will increase the value of the response variable Y by the slope of X_i. The R^2 statistic is generally used in regression models to describe how much variability of the data is explained by the model. For multivariable linear regression models, the variability of the model can be evaluated by the adjusted R^2 statistic, which is an adjustment of the R^2 based on the number of observations and predictors in the model. Higher adjusted R^2 is an indicator of a better fit of the model to the data and the proportion of the data that can be explained by the model.

The models were developed using a manual selection process informed by the results of the correlation analysis. Significantly associated independent variables were not included in the same model.

9.3.1 Model Selection Process

Since the independent variables show a significant intercorrelation, the team decided to start with single variable models and include other variables on the basis of non-existent co-linearity and improving the adjusted-R^2. The single variable models are based on NOISE, XSPD_AVE and YR. The following are the single variable models for dependent variables INT and INTR.

Table 9-4 Single Variable Models for Intervention and Intervention-Risky Models

Single Variable Intervention Models

Model 1a	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
NOISE	0.0773	0.0113	6.83	0	0.0546	0.1000
Constant	0.0241	0.0063	3.84	0	0.0115	0.0367
Prob>F	0					
R^2	0.4829					
Adj. R^2	0.4725					

Model 2a	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
YR	-0.0469	0.0248	-1.89	0.064	-0.0967	0.0028
Constant	0.0756	0.0162	4.66	0	0.0430	0.1082
Prob>F	0.064					
R^2	0.0669					
Adj. R^2	0.0483					

Model 3a	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
XSPD_AVE	0.0042	0.0014	3.06	0.004	0.0014	0.0069
Constant	-0.0333	0.0273	-1.22	0.229	-0.0882	0.0216
Prob>F	0.0035					
R^2	0.158					
Adj. R^2	0.1412					

Single Variable Intervention-Risky Models

Model 1b	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
NOISE	0.1561	0.0313	4.99	0	0.0932	0.2189
Constant	0.1216	0.0174	7.01	0	0.0868	0.1565
Prob>F	0					
R^2	0.3323					
Adj. R^2	0.319					

Model 2b	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
YR	-0.1474	0.0589	-2.5	0.016	-0.2656	-0.0292
Constant	0.2568	0.0386	6.66	0	0.1793	0.3342
Prob>F	0.0155					
R^2	0.1115					
Adj. R^2	0.0938					

Model 3b	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval.]	
XSPD_AVE	0.0093	0.0034	2.75	0.008	0.0025	0.0161
Constant	-0.0106	0.0675	-0.2	0.875	-0.1463	0.1250
Prob>F	0.0082					
R^2	0.1316					
Adj. R^2	0.1143					

Table 9-4 shows the single variable models for intervention and intervention-risky predictions. Based on Table 9-4, the model with NOISE variable as the predictor has the highest R^2 and adjusted R^2 (0.48, 0.47 respectively for intervention and 0.33, 0.31 respectively for intervention-risky) among the rest of the models. The model with YR (yield rate) has the lowest R^2 and adjusted R^2 (0.06, 0.05 respectively for intervention model and 0.11, 0.09 respectively for the intervention-risk model). It seems that variable NOISE is a better predictor of the dependent variables for both intervention and intervention-risky models. Therefore more models with additional variables (two-variable, three-variable and four-variable models) are developed. Several other models with YR and XSPD_AVE variables are also developed and presented in Table 9-5. Table 9-5 shows the models that include NOISE have higher adjusted R^2 compared to the rest of the models. The model with the highest adjusted R^2 is Model 12 with variables NOISE, XPSD_AVE, SIGHT_D and RBTX (adjusted $R^2 = 0.54$). However, XSPD_AVE and RBTX are not statistically significant at $p<0.10$. The next best models are models 10 and 13 with adjusted $R^2 = 0.53$. Model 10 includes NOISE ($p<0.005$), XSPD_AVE ($p<0.10$) and SIGHT_D ($p<0.005$) and all variables are statically significant. Model 13 includes NOISE, XSPD_AVE, SIGHT_D, N2 and RBTX and neither N2, nor RBTX are statistically significant at $p<0.10$. Therefore the final suggested model for predicting intervention rates is Model 10 as shown in Table 9-6. It is important to note that the limitation of the model is that it should be used for speeds greater than 10 mph.

Table 9-7 shows all the intervention-risky models developed by combining various variables in the models. Similar to the intervention models, the intervention-risky models that include NOISE as one of the independent variables have higher adjusted R^2 than the rest of the models. Models 10b and 13b both have adjusted R^2 of 0.38 and 0.53, respectively. However, Model 10b is consistent with the final proposed model for intervention rate and include variables NOISE ($p<0.005$) , XSPD_AVE($p=0.11$) and SIGHT_D ($p<0.10$). Model 13b includes NOISE, XSPD_AVE, SIGHT_D, N2 and RBTX, however, XSPD_AVE, N2 and RBTX are not statistically significant in this model. Therefore, the final proposed model for intervention-risky prediction is model 10b as shown in Table 9-8. It is important to note that the limitation of the model is that it should be used for speeds greater than 10 mph.

Table 9-5 Intervention Models

INT=	NOISE	YR	XSPD_AVE	SIGHT_D	OLDEC	N2	RBTX	Constant	Prob>F	R^2	Adj. R^2
Model 1a	0.0773**							0.0241	0	0.483	0.473
Model 2a		-0.0469+						0.0756	0.064	0.067	0.048
Model 3a			0.0042**					-0.0333	0.0035	0.158	0.141
Model 4a	0.0746**				0.0047			0.0229	0	0.484	0.463
Model 5a	0.069**			0.0243*				0.0187	0	0.527	0.507
Model 6a	0.0703**		0.0021+					-0.0149	0	0.52	0.5
Model 7a	0.0749**	-0.0151						0.0337	0	0.489	0.469
Model 8a	0.0678**	0.0234*		0.0234*				0.0252	0	0.529	0.5
Model 9a	0.0651**		0.002+	0.0243**	-0.0049			-0.0175	0	0.56	0.523
Model 10a	0.0629**		0.002+	0.023**				-0.0177	0	0.559	0.531
Model 11a	0.062**		0.0018+	0.0235*		0.0081		-0.0196	0	0.564	0.527
Model 12a	0.0575**		0.0016	0.022+			0.0162	-0.0142	0	0.577	0.541
Model 13a	0.0574**		0.0016	0.0223+		0.0042	0.0149	-0.0155	0	0.578	0.532
Model 14a			0.0024+	0.0362*		0.0048+	0.0314	-0.0262	0.0001	0.381	0.328
Model 15a			0.0036*	0.0412**				-0.0347	0.0002	0.296	0.268
Model 16a			0.0033*		0.0331*			-0.0309	0.0008	0.253	0.222
Model 17a		-0.0317		0.0429**				0.0526	0.0028	0.214	0.181

+ $p<0.10$, *$p<0.05$, **$p<0.005$

Table 9-6 Final Intervention Model

INT=	Coefficient	Std. Err.	t	P>|t|	[95% Conf.	Interval.]
NOISE	0.0629	0.0118	5.34	0	0.0393	0.0866
XSPD_AVE*	0.0020	0.0011	1.87	0.067	-0.0001	0.0041
SIGHT_D	0.0230	0.0112	2.06	0.044	0.0006	0.0455
Constant	-0.0177	0.0204	-0.86	0.392	-0.0588	0.0234
Prob>F	0.00					
R-squared	0.558	*Model Limitation: XSPD_AVE >=10 mph				
Adj. R-Squared	0.531					

Table 9-7 Intervention-Risky Models

INT=	NOISE	YR	XSPD_AVE	SIGHT_D	OLDEC	N2	RBTX	Constant	Prob>F	R^2	Adj. R^2
Model 1b	0.0773**							0.0241	0.0000	0.4829	0.4725
Model 2b		-0.0469						0.0756	0.0640	0.0669	0.0483
Model 3b			0.0042*					-0.0333	0.0035	0.1580	0.1412
Model 4b	0.0746**				0.0047			0.0229	0.0000	0.4844	0.4633
Model 5b	0.0690**			0.0243*				0.0187	0.0000	0.5265	0.5071
Model 6b	0.0703**		0.0021+					-0.0149	0.0000	0.5196	0.5000
Model 7b	0.0749**	-0.0151						0.0337	0.0000	0.4893	0.4685
Model 8b	0.0678**	0.0234		0.0234+				0.0252	0.0000	0.5291	0.4997
Model 9b	0.0651**		0.0020	0.0243	-0.0049+			-0.0175	0.0000	0.5602	0.5228
Model 10b	0.0629**		0.0020+	0.0230+				-0.0177	0.0000	0.5588	0.5312
Model 11b	0.0620**		0.0018*	0.0235		0.0081		-0.0196	0.0000	0.5642	0.5271
Model 12b	0.0575**		0.0016+	0.0220			0.0162	-0.0143	0.0000	0.5769	0.5409
Model 13b	0.0574**		0.0016*	0.0223		0.0042	0.0149	-0.0155	0.0000	0.5782	0.5323
Model 14b			0.0024+	0.0362*		0.0048	0.0314	-0.0262	0.0001	0.3809	0.3283
Model 15b			0.0036*	0.0412+				-0.0347	0.0002	0.2963	0.2676
Model 16b			0.0033*		0.0331*			-0.0309	0.0008	0.2528	0.2223
Model 17b		-0.0317*		0.0429**				0.0526	0.0028	0.2135	0.1814

+ $p<0.1$, * $p<0.05$, ** $p<0.005$

Table 9-8 Final Proposed Intervention-Risky Model

INTR=	**Coefficient**	**Std. Err.**	**t**	**P>|t|**	**[95% Conf.**	**Interval.]**
NOISE	0.1191	0.0329	3.62	0.001	0.0529	0.1853
XSPD_AVE*	0.0049	0.0030	1.64	0.108	-0.0011	0.0109
SIGHT_D	0.0617	0.0312	1.98	0.054	-0.0010	0.1245
Constant	0.0183	0.0572	0.32	0.751	-0.0967	0.1332
Prob>F	0					
R-squared	0.4174	*Model Limitation: XSPD_AVE >=10 mph				
Adj. R-Squared	0.381					

9.4 Summary

Multivariable linear regression models were generated to predict the rate that blind pedestrians may make bad crossing decisions that result in intervention events and intervention and risky events. Two separate models were generated to predict the intervention rates (associated with dangerous crossing decisions) and total of intervention and risky crossing decisions. Both of these models include noise level at the crosswalk (0 or low levels of noise and 1 for high levels of noise), average speed of the vehicle at the crosswalk (continuous variable for values greater than 10 mph) and sight distance (0 if pedestrian sight distance is provided and 1 if it is not provided). Figure 9-1 plots the predicted intervention rates vs. the field observed intervention rates. Figure 9-2 shows the predicted intervention-Risky rates vs. the field observed intervention-risky rates.

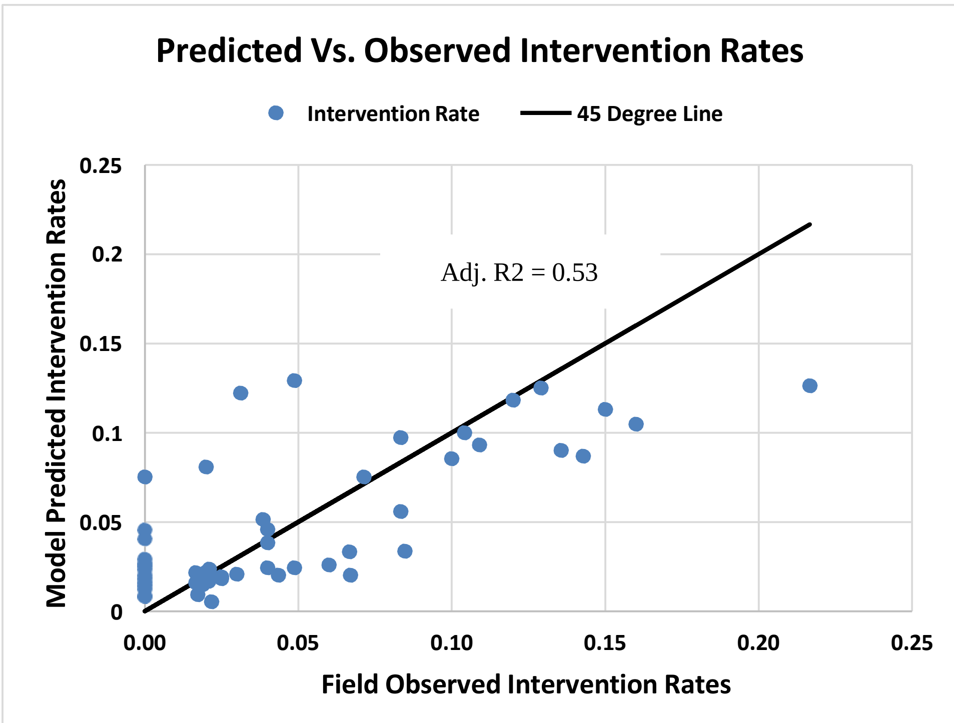


Figure 9-1 Plot of Predicted Intervention Rates vs. Observed Intervention Rates

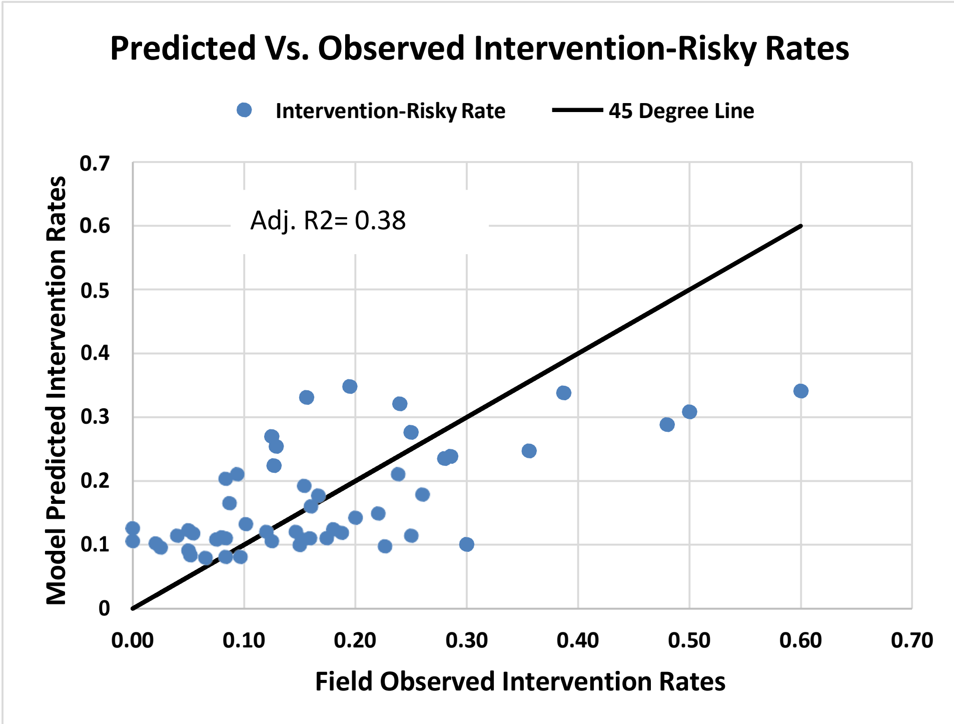


Figure 9-2 Plot of Predicted Intervention-Risky Rates vs. Observed Intervention-Risky Rates

11 APPENDIX D: CROSSING SIGHT DISTANCE DETAILS

11.1 Introduction

This report presents the results of research to develop guidance for designing crosswalks at modern roundabout and channelized turn lanes (CLTs) to assist pedestrians with vision disabilities. The issues of pedestrian behavior and safety at roundabout crosswalks are not well understood, particularly for pedestrians with sensory or mobility impairments. A previous study shows that blind pedestrians miss more crossing opportunities and make riskier judgments than sighted pedestrians (Ashmead et al., 2005). The main considerations include the driver sight distance needs toward the conflicting traffic stream (roundabout circle and channelized turn lane downstream traffic), as well as sight distances toward a pedestrian waiting on the curb or on a splitter island. The purpose of this research is to come up with the recommended design that can minimize vehicular speed, while maximizing sight distances to the crosswalk, so that no (additional) treatment may be necessary. This report documents and presents the results of research to develop guidance for the application of crossing solutions at roundabout and channelized turn lanes and later in this report the alternative approaches for designing an applicable pedestrian crossing sight distance will be discussed.

The issue of pedestrian safety at roundabout crosswalks remains generally unstudied. Because blind pedestrians cannot use visual information to identify approaching vehicles and to make crossing decisions at traditional intersections, they typically rely on predictable patterns of vehicle movement that are usually created by traffic control devices. At modern roundabout intersections, these techniques for making non-visual street-crossing judgments are not useful because traffic flows unpredictably in and out of the roundabout (Retting et al., 2001).

Channelized turn lanes (CTLs) are a common treatment applicable for signalized intersections with high volumes of right-turning vehicles that experience excessive delay due to traffic signals; they allow heavy right-turning movement to bypass the main intersection (FHWA, 2000). Larger turn radii and higher speeds are a safety issue for pedestrians. Channelized turn lanes resemble roundabouts in geometry and pose similar challenges to blind pedestrians attempting to cross the road. In both designs, traffic may be free flowing or may yield to circulating vehicles at roundabouts or to downstream traffic at CTLs. Crosswalks at CTLs are usually unsignalized.

The review of the literature confirmed that pedestrian crossing sight distance has not been explored to the same degree that vehicle sight distance has been investigated. While similar in concept, there are a variety of pedestrian characteristics, site geometry, and crosswalk location that require separate crossing sight distance design procedures. In the AASHTO publication, A Policy on the Geometric Design of Highways and Streets, also known as the “Green Book,” many design principles are based on the concept of vehicle sight distance calculations. In details, AASHTO distinguishes three types of sight distance: (1) stopping sight distance, (2) intersection sight distance, and (3) decision sight distance. These sight distances are used to guide the design of features such as minimum radii for horizontal and vertical curves, or to limit landscaping and sight obstructions at intersections and serve to reduce impedances to the driver’s line of sight (AASHTO, 2011). The resulting design principles are also reflected in roundabout design guidelines (Rodegerdts et al., 2010), and apply equally to CTLs. Pedestrian sight distance is currently not considered in the Green Book.

11.2 Methodology

For the purpose of this research, the methodology developed to determine crossing sight distance adequacy at a roundabout and CTLs has been adapted from the sight distance performance check for vehicles at roundabouts *from NCHRP Report 672: Roundabouts: An Informational Guide* (Rodegerdts et al., 2010), calculations and definitions from the AASHTO “Green Book” (AASHTO, 2011), and roundabout segment methodology in Chapter 30 of the 2010 Highway Capacity Manual (TRB, 2010).

In this report of the results of research under NCHRP 3-78b, crossing sight distance is introduced as the distance required by pedestrians to recognize the presence of conflicting vehicular traffic and determine crossing opportunities at intersections and roundabouts. The estimation of crossing sight distance requires several input variables and assumptions to perform the calculations. First, the calculation requires the estimation of a prevailing vehicle speed. This speed is estimated from site geometry (design radii), as well as speed prediction equations described in next section. Second, the calculation requires the estimation of a crossable gap time, which is a function of crossing distance, pedestrian walking speed, and any decision latency.

For this research, the distance is established through sight triangles that allow a pedestrian to evaluate potential conflicts with approaching vehicles. Similarly, the resulting sight triangles also assure that the driver has a clear view of a pedestrian waiting to cross or approaching the crosswalk. For pedestrians who are blind, the crossing sight distance applies in that any visual obstructions are also expected to impact the ability to hear approaching vehicles without sound obstructions or deflections. Although sight triangles are traditionally bound by linear vehicle paths, the roadway geometry of roundabouts and CTLs is non-linear as illustrated in Figure 11-1.

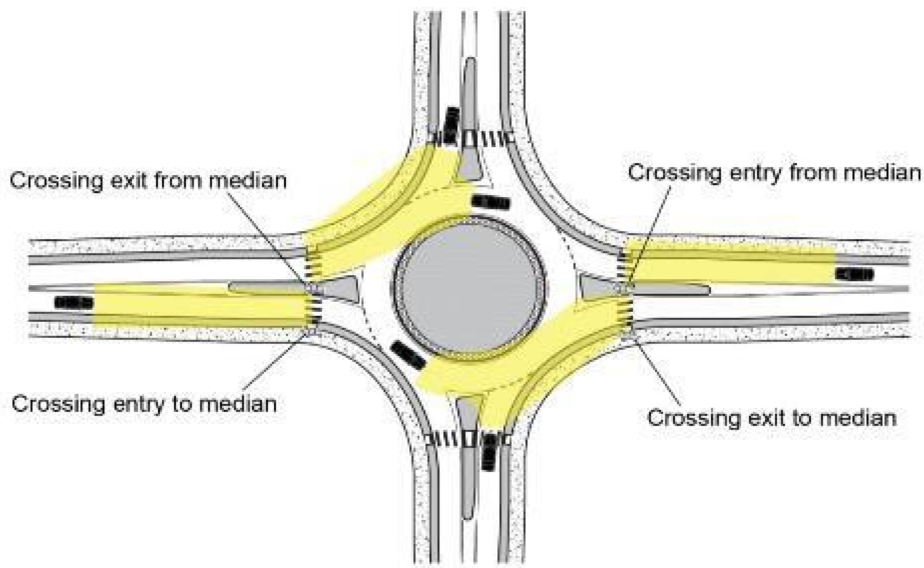


Figure 11-1: Pedestrian Sight Triangles for Each Crossing Location

Therefore, sight distances are derived along the curvature of conflicting vehicular travel paths using the estimated vehicle speed and crossable gap times. This provides the distance for vehicles to travel along a path toward the crosswalk at their current speed in the amount of time needed for a pedestrian to cross the road safely. In other words, adequate crossing sight distance assures that a pedestrian can identify vehicles far enough away to provide sufficient time to cross the road. Adequate crossing sight distance also ensures that drivers can see pedestrians as they step off the curb and into the roadway with sufficient time to react. It also ensures that pedestrians who are blind, who have unimpaired hearing, are likely to be able to hear approaching vehicles well enough to make safe judgments regarding when to begin crossing.

11.3 Data Collection

The research team evaluated a list of potential study sites and selected those that were deemed suitable for further field investigation. Under the support of NCHRP 3-78B, the team proposed the application of a newly developed study protocol--enhanced based on the lessons learned in NCHRP 3-78A. Through studies conducted in this research, and supported by earlier accessibility work, this team sought to identify what aspects of geometry contribute to enhanced accessibility, and to document these findings. Examples include the inscribed diameter, R1 through R5 radii of a roundabout as described in NCHRP Report 672, the relative location of the crosswalk to the circulating lane, the shape of the splitter island at a channelized turn lane, and the curve radii in that channelized turn lane. In addition to geometry audits, the team performed speed studies of free-flow vehicles entering and exiting the roundabout to gain insight on the expected speed patterns in the vicinity of the crosswalk, and the effectiveness of design features (such as RCW) to reduce speeds. With the timing of this project, there was a unique opportunity to study the availability of existing treatments in addition to non-treatment sites across the country for an efficient and timely completion of data collection

11.4 Data Analysis and Framework

This section describes the data and geometry analysis of the RBT and CTL sites. As mentioned in previous sections of this report, the method and equations that were used for calculation of crossing sight distance are adopted from AASHTO, NCHRP Report 672, and HCM 2010. The concept and detailed calculation approaches of crossing sight distance for all the study sites is discussed in the following sections.

11.4.1 Approach 1: HCM Gap Acceptance Methodology

In our first approach to calculate the minimum intersection sight distance, two parameters were measured based on the collected data from the study fields. The first parameter is the critical headway, $t_{n,c}$, for the pedestrian. The critical headway describes the minimum amount of time necessary for a pedestrian to cross the roadway. The critical headway calculation is directly derived from the pedestrian analysis method covered in the two-way stop-controlled intersection methodology of the Highway Capacity Manual 2010 (TRB, 2010).

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

Where,

L_n = crosswalk length for a specific traffic stream, ft;

S_p = average pedestrian walking speed, ft/s, could be measured in the field with a maximum value of 3.5 ft/s;

t_s = pedestrian start-up time and end clearance time, s.

In the context of this analysis, the pedestrian start-up and end clearance time estimate should include any decision latency by a blind pedestrian. In field observations and direct comparisons of decision-making by blind and sighted pedestrians at CTLs (Schroeder et al., 2006), it is evident that a sighted person makes the crossing decision much more quickly compared to a blind person, who typically waits for the vehicle sound to subside before making a decision.

The second parameter is the vehicle speed. The analyst can either measure or make an assumption about the speed, V, of vehicles along the approach of interest. Using the speed (V) and critical pedestrian headways ($t_{n,c}$), the length of the conflicting vehicle paths (d) are calculated using the equations below.

$$d_1 = (1.467)\,(V1,_{entering})\,(t_{1,c})$$

$$d_{2,e} = (1.467)\,(V2,_{entering})\,(t_{2,c})$$

$$d_{2,c} = (1.467)\,(V2,_{circulating})\,(t_{2,c})$$

$$d_{3,e} = (1.467)\,(V3_{,entering})\,(t_{3,c})$$

$$d_{3,c} = (1.467)\,(V3_{,circulating})\,(t_{3,c})$$

$$d_4 = (1.467)\,(V4_{,entering})\,(t_{4,c})$$

Where,

d_1 = distance along entry leg upstream of the entry crosswalk for crossing from curb, ft;

$d_{2,e}$ = distance along previous entry upstream of the exit crosswalk for crossing from island, ft;

$d_{2,c}$ = distance along circulating lane upstream of the exit crosswalk for crossing from island, ft;

$d_{3,e}$ = distance along previous entry upstream of the exit crosswalk for crossing from curb, ft;

$d_{3,c}$ = distance along circulating lane upstream of the exit crosswalk for crossing from curb, ft;

d_4 = distance along entry leg upstream of the entry crosswalk for crossing from island, ft;

$V_{n,stream}$ = design speed of conflicting movement, mph;

$t_{n,c}$ = critical headway required by a pedestrian crossing a specific traffic stream, depends on the number of lanes and lane width.

Figure 11-2 shows the necessary sight distance, d, for each crossing location at the entry and exit of a roundabout (NCHRP 3-78b)

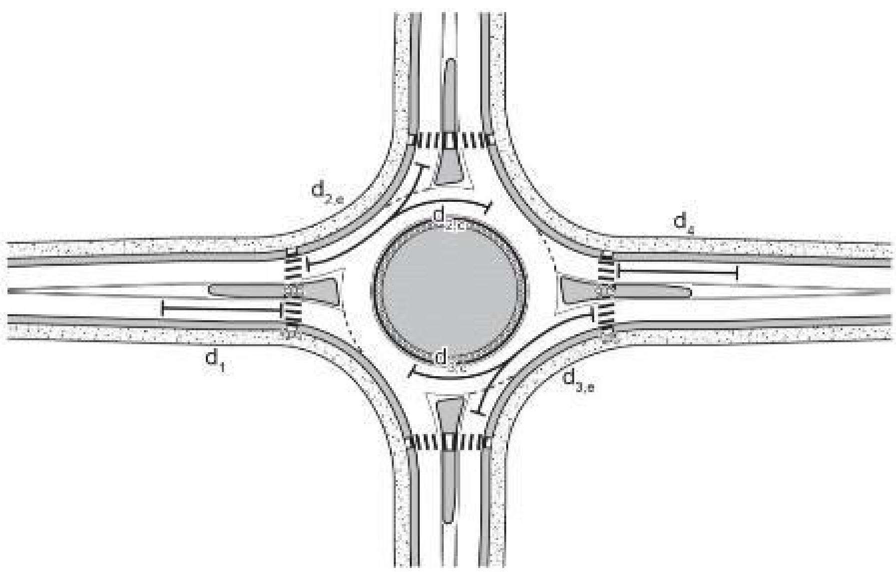


Figure 11-2: Minimum Sight Distance Along the Actual Path

Because pedestrians crossing at CTLs are conceptually similar to those crossing at roundabouts, the same parameters of critical headway and vehicle speed were measured using the aforementioned equations for the distance along the approach upstream of the crosswalk for crossing from curb at CTLs.

In this step, necessary sight distance was measured using the existing geometric measurement and 85 percentile and average speed collected from the filed study. The team assumed 3.5 feet per second walking speed and 2 second lost time. Figure 11-3 shows the calculated sight distance, d, for each crossing location at the entry and exit for the Cemetery Road and Main Street roundabout in Hilliard, OH.

$t_{n,c} = (L_n / S_p) + t_s$	Sight Distance (Avg Speed)	Sight Distance (85% Speed)	Crosswalk Length, ft (Ln)	$S_{p\ (ft/sec)}$	ts (sec)	Critical Headway (tn,c)	Avg Speed (mph)	85 % Speed (mph)
$\mathbf{d_1}$ = (1.467) ($V_{1,entering}$) ($t_{1,c}$)	**288**	**263**	26	3.5	2	9.43	20.8	19
$\mathbf{d_{2,e}}$ = (1.467) ($V_{2,entering}$) ($t_{2,c}$)	**206**	**302**	23	3.5	2	8.57	16.4	24
$\mathbf{d_{2,c}}$ = (1.467) ($V_{2,circulating}$) ($t_{2,c}$)	**262**	**302**	23	3.5	2	8.57	20.8	24
$\mathbf{d_{3,e}}$ = (1.467) ($V_{3,entering}$) ($t_{3,c}$)	**201**	**227**	21.5	3.5	2	8.14	16.8	19
$\mathbf{d_{3,c}}$ = (1.467) ($V_{3,circulating}$) ($t_{3,c}$)	**201**	**227**	21.5	3.5	2	8.14	16.8	19
$\mathbf{d_4}$ = (1.467) ($V_{4,entering}$) ($t_{4,c}$)	**331**	**386**	24	3.5	2	8.86	25.5	29.7

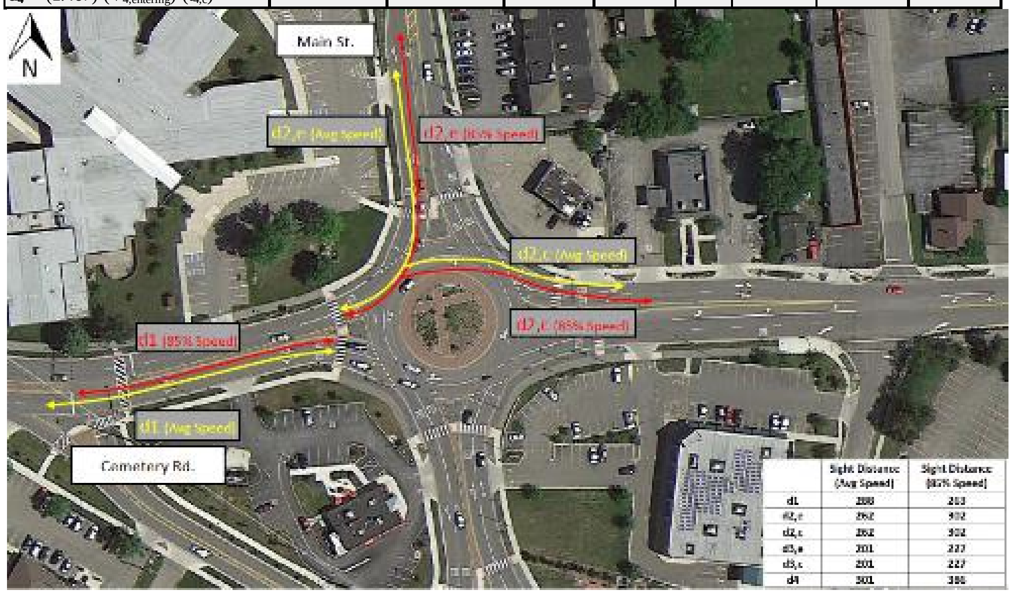


Figure 11-3: West Approach at Cemetery Road at Main Street, Hilliard, OH

After applying this method to all the roundabouts and CTLs locations, the team observed longer sight distances than they expected. The team decided to use a different approach for further analysis.

11.4.2 Approach 2

The team proposed a second, alternative approach to calculate the crossing sight distance that was based on a variation of stopping sight distance as presented AASHTO “Green Book.” For each approach, the team calculated five crossing sight distances using the same equations used in the previous method and checked which method would give us the minimum distance. These methods are as follows:

1. Gap Acceptance Distance, Full Crossing Width, 2-second reaction time
2. Gap Acceptance Distance, Full Crossing Width, 0-second reaction time
3. Gap Acceptance Distance, Crossing Width minus 1/2 lane, 0-second reaction time
4. Yield Reaction Distance, 5 second deceleration, 2.5 second reaction time
5. Yield Reaction Distance, 5 second deceleration, 1 second reaction time

The average collected field speed and the existing geometric measurement were used in this step. Figure 11-4 shows the calculated sight distance, d, for each approach, entry and exit, at the Cemetery Road and Main Street roundabout in Hilliard, OH.

Entry	d C1	d C2	d C3	Entry	d C4	d C5
Reaction Time (sec)	2	0	0	Reaction Time (sec)	1	2.5
Crossing Width (ft)	24	24	18	Deceleration Rate (ft/s^2)	5	5
Vehicle Speed (mph)	Gap Acceptance Distance (ft)			Vehicle Speed (mph)	Yield Reaction Distance (ft)	
16.8	219	169	127	16.8	55	92

Exit	d C1	d C2	d C3	Exit	d C4	d C5
Reaction Time (sec)	2	0	0	Reaction Time (sec)	1	2.5
Crossing Width (ft)	22	22	16.5	Deceleration Rate (ft/s^2)	5	5
Vehicle Speed (mph)	Gap Acceptance Distance (ft)			Vehicle Speed (mph)	Yield Reaction Distance (ft)	
25.5	311	236	177	25.5	107	164

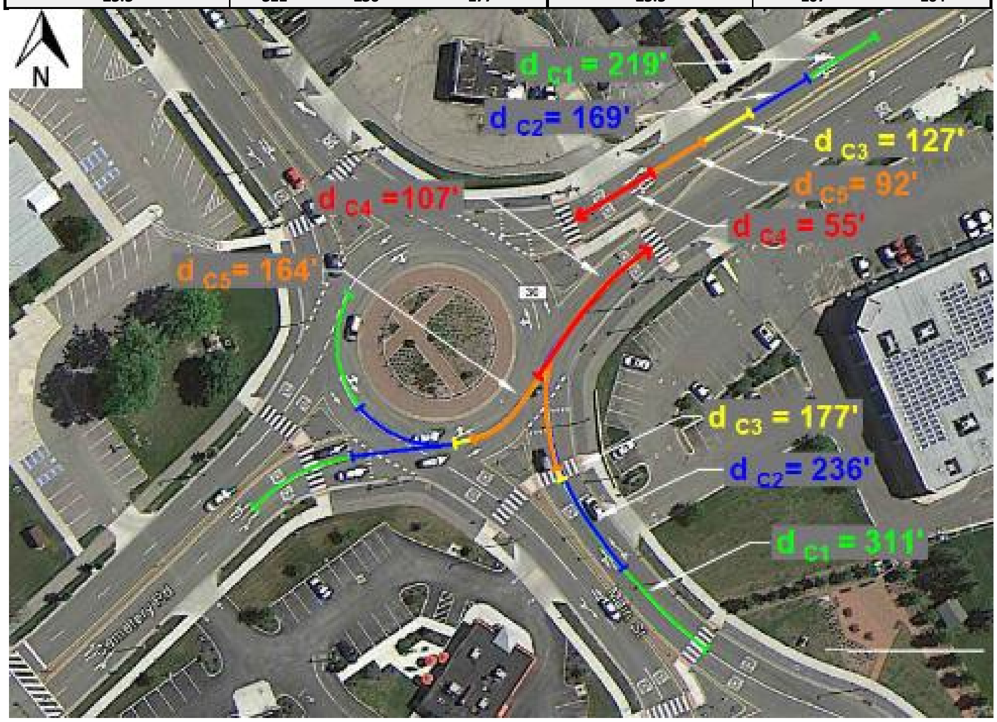


Figure 11-4: West and East Approach at Cemetery Road at Main Street, Hilliard, OH

The same parameters of critical headway and vehicle speed were measured using the aforementioned equations for the distance along the approach upstream of the crosswalk for crossing from curb at CTLs .

11.4.3 Approach 3: Fastest Path Method

In this approach, speeds were predicted using the fastest path method presented in NCHRP Report 672. The fastest path is the smoothest and flattest path possible for a single vehicle ignoring all the lane markings and in the absence of other vehicles. In NCHRP Report 672, the fastest path is described as a path that vehicles travel through the entry, circulating around the center island, and out of the exit. It is important to know that the fastest path methodology does not represent expected vehicle speed, but rather assumed reasonable entry speed for design purposes. The actual speed can be varied based on individual abilities and tolerance for gravitational forces exit (NCHRP 672). Figure 11-5 illustrates the five important path radii that were checked and measured in this approach. R_1, is the entry path radius and the minimum radius on the fastest through path prior to the entrance line. R_2, is the circulating path radius and the minimum radius on the fastest through path around the central island. R_3, is the exit path radius and the minimum radius on the fastest through path into the exit. R_4, is the left-turn path radius and the minimum radius on the path of the conflicting left-turn movement. R_5 is the right turn path radius and the minimum radius on the fastest path of a right-turning vehicle. These radii paths are not the same as the curb radii path and R_1 through R_5 measured using the vehicle centerline in its path through the roundabout.

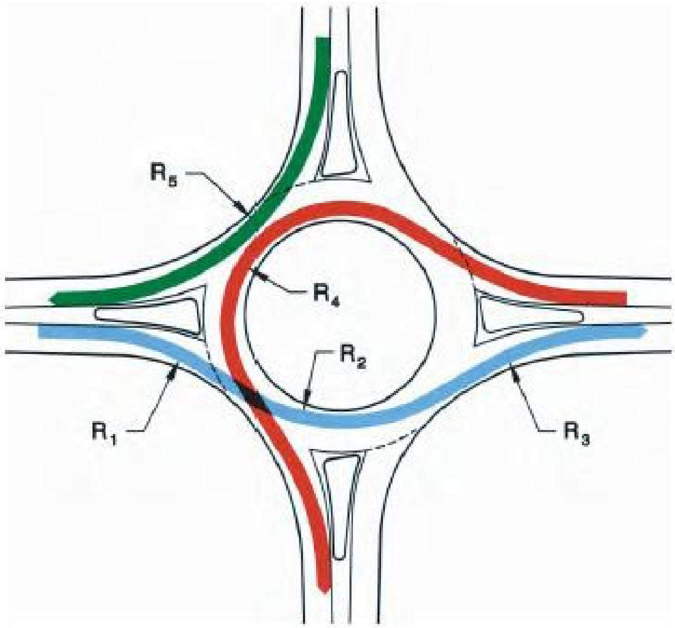


Figure 11-5: Fastest Path Illustration (NCHRP 672)

The radii paths were measured using AutoCAD software by drawing a fitted curve along each path for entry, exiting, and circulating movements. All these radii path measurements were used to predict speed using the following equations that were adopted by AASHTO "Green Book" and presented in NCHRP 672.

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

$$V = 3.4614R^{0.3673}\text{, for } e = -0.02$$

Where;

V = predicted speed, mph;

R = radius of curve, ft; and

e = superelevation, ft/ft.

These equations were used only to estimate the entry vehicle speed (V_1), exiting speed (V_3), and right turn speed at the roundabout. In order to calculate the circulating speed (V_2) and (V_4), the circulating path radius (R_2) and the left-turn path radius (R_4) were calculated using equation presented in HCH 2010 Chapter 30.

$$r_{c,th} = \frac{ICD}{2} + \frac{N_c w_c}{2}$$

Where:

$r_{c,th}$ = average radius of circulating path of through movement (ft), ICD = inscribed circle diameter (ft),

N_c = number of circulating lane(s), and

w_c = average width of circulating lane(s) (ft).

This equation provided the average radius of circulating path by assuming that the radius of circulating path occupies the centerline of the circulating roadway is equal to half of the central island plus half of the total width of the circulatory roadway. The center line path was measured around the circular movement and, for the ease of calculation, the second parameter in the calculation was not used in our measurement.

The speeds associated with this radius for circulating movement were calculated from the following equation from NCHRP Report 572, which assumes a negative cross slope of the circulatory roadway of -0.02.

$$S_c = 3.4614 {r_{c,th}}^{0.3673}$$

Where:

S_c = circulating speed (mi/h), and

$r_{c,th}$ = average radius of circulating path of through movement (ft).

To better predict actual entry speeds, the following equation was used for deceleration of vehicles from the entering R_1 speed to the circulating R_2 speed. Using a deceleration factor would promote a safe design by controlling entry speed. This equation was provided in NCHRP Report 672.

$$V_1 = \min \begin{Bmatrix} V_{1pbase} \\ \frac{1}{1.47}\sqrt{(1.47V_2)^2 + 2a_{12}d_{12}} \end{Bmatrix}$$

Where:

V_1 = entry speed, mph;

V_{1pbase} = V_1 speed predicted based on path radius, mph;

V_2 = circulatory speed for through vehicles predicted based on path radius, mph;

a_{12} = deceleration between the point of interest along V_1 path and the midpoint of V_2 path = 4.2 ft/s^2; and

d_{12} = distance along the vehicle path between the point of interest along V_1 path and the midpoint of V_2 path, ft.

A similar approach can be used for the exiting speed based on the exit radius R_3. At the locations with a large radius exit, the measured R_3 can be so large that the acceleration characteristics of the vehicle will govern the actual speeds that can be achieved. To control the exit speed, the following equation was used from NCHRP Report 672;

$$V_3 = \min \begin{Bmatrix} V_{3pbase} \\ \frac{1}{1.47}\sqrt{(1.47V_2)^2 + 2a_{23}d_{23}} \end{Bmatrix}$$

Where;

V_3 = exit speed, mph;

V_{3pbase} = V_3 speed predicted based on path radius, mph;

V_2 = circulatory speed for through vehicles predicted based on path radius, mph;

a_{23} = acceleration between the midpoint of V_2 path and the point of interest along V_3 path = 6.9 ft/s^2; and

d_{23} = distance along the vehicle path between midpoint of V_2 path and point of interest along V_3 path, ft.

After estimating the speed for all the movements along each path and in order to obtain the through and left-turn movement speed, the average of total speed for entry and circulating vehicle (V_2+V_3+V_4/3) were measured. The result of this approach is shown in Table 11-1. Like the first method described in this chapter, we assumed 3.5 feet per second walking speed and 2 second reaction time.

Table 11-1: Results of Sight Distance Calculation (Novi, MI)

Maple Rd and Farmington Rd., Novi, MI						
	East Exit (L & T)	East Exit (R)	East Entry	North Exit (L & T)	North Exit (R)	South Entry
R1	118	-	184	99	-	150
R2 & R4	104	-	104	104	-	104
R3	122	-	-	113	-	-
R5	-	166	-	-	105	-
Reaction Time (sec)	2	2	2	2	2	2
Crossing Width (ft)	36	36	32	23	23	21
Vehicle Speed (mph)	21	24	25	21	20	23
Gap Acceptance Distance (ft)	372	433	410	260	252	270

This equation generally provides a reasonable prediction for the left-turn and through movement circulating speed. Because the presence of raised crosswalks (RCW) in some of the study sites could govern the speed that can be reached at the entry and the exit, we measured and recalculated the crossing sight distance using a new approach. The three estimated speeds based on the fastest path method, deceleration/acceleration, and observed speed effect by raised cross walk were compared and the minimum of these three speeds was selected. Section 11.7 provides an example of this calculation for the sites that have raised crosswalks. The following table shows the new speed estimation for one of the study sites that was impacted by RCW.

Table 11-2: Results of Sight Distance Calculation (Novi, MI)

Maple Rd and Farmington Rd., Novi, MI						
	East Exit (L & T)	East Exit (R)	East Entry	North Exit (L & T)	North Exit (R)	South Entry
R1	118	-	184	99	-	150
R2 & R4	104	-	104	104	-	104
R3	122	-	-	113	-	-
R5	-	166	-	-	105	-
Reaction Time (sec)	2	2	2	2	2	2
Crossing Width (ft)	36	36	32	23	23	21
Vehicle Speed (mph)	19	13	13	19	13	13
Gap Acceptance Distance (ft)	336	235	213	235	164	153

This method was also applied to measure CTL crossing sight distance with raised crosswalks. Additional table and sight distance measurements for all other sites presented in Section 11.6 and Section 11.7.

11.5 Summary

Summarizing the discussion above, the team proposed a total of 20 sight distance pedestrian approaches to be analyzed for roundabouts and channelized turn lanes, with some of them having treatment installations such as raised crosswalks to reduce the vehicle speed in five different states across the United States. Roundabouts and CTLs present similar challenges to pedestrians who are blind, since they both have yield controlled approaches to the intersection. However, distinct differences in traffic patterns and design and geometric attributes between roundabouts and CTLs result in unique challenges to define these performance checks for each type of facility. The methodology developed to determine crossing sight distance adequacy at a roundabout or CTL was adapted from the sight distance performance check for vehicles at roundabouts. Since there has not been enough study done on the concept of blind pedestrian crossing sight distance, several alternative solutions were tried, and appropriate sight distance measurements that could be recommended as a design guideline for the future construction are proposed.

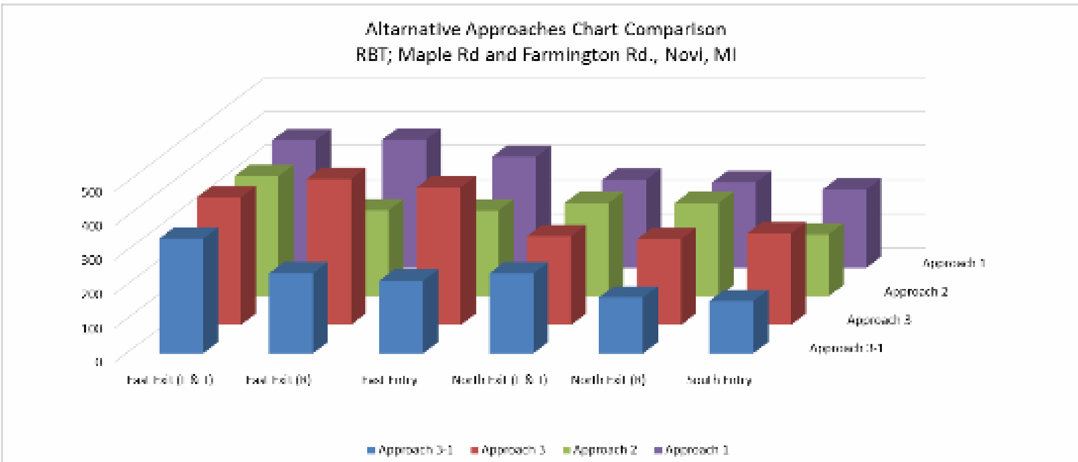


Figure 11-6: Comparison Chart of All Three Approaches (RBT, Novi, MI)

As shown in Figure 11-6, the result of measuring fastest path method that was explained previously and considering the existing raised crosswalk effect leads to a lower sight distance path. The resulting finding from the fastest path method gives us a conservative sight distance length that will help pedestrians to determine when to accept the gap and thus will make crossing safer for them.

11.6 Sight Distance Calculation Details

Maple Rd and Farmington Rd., Novi, MI							
Approach Leg: East Exit							
ICD (ft)	R1	R2	R3	R4	R5	d12	d23
251	118	104	122	104	166	180	165
	Radius	decel	accel	Field RCW	Min		
V1	21	33			21		
V2 (Sc)	20	33			20		
V3	21			15	15		
V4	20	33			20		
V5	24			13	13		
T & L	19						
R	13						
Approach Leg: North Exit							
ICD (ft)	R1	R2	R3	R4	R5	d12	d23
251	99	104	113	104	105	200	165
	Radius	decel	accel	Field RCW	Min		
V1	19	35			19		
V2 (Sc)	20	33			20		
V3	20			15	15		
V4	20	33			20		
V5	20			13	13		
T & L	19						
R	13						
Approach Leg: South Entry							
ICD (ft)	R1	R2	R3	R4	R5	d12	d23
251	150	104				160	
	Radius	decel	accel	Field RCW			
V1	23	32		13	13		
V2 (Sc)	20						
T	13						
Approach Leg: East Entry							
ICD (ft)	R1	R2	R3	R4	R5	d12	d23
251	184	104				180	
	Radius	decel	accel	Field RCW			
V1	25	33		13	13		
V2 (Sc)	20						
T	13						

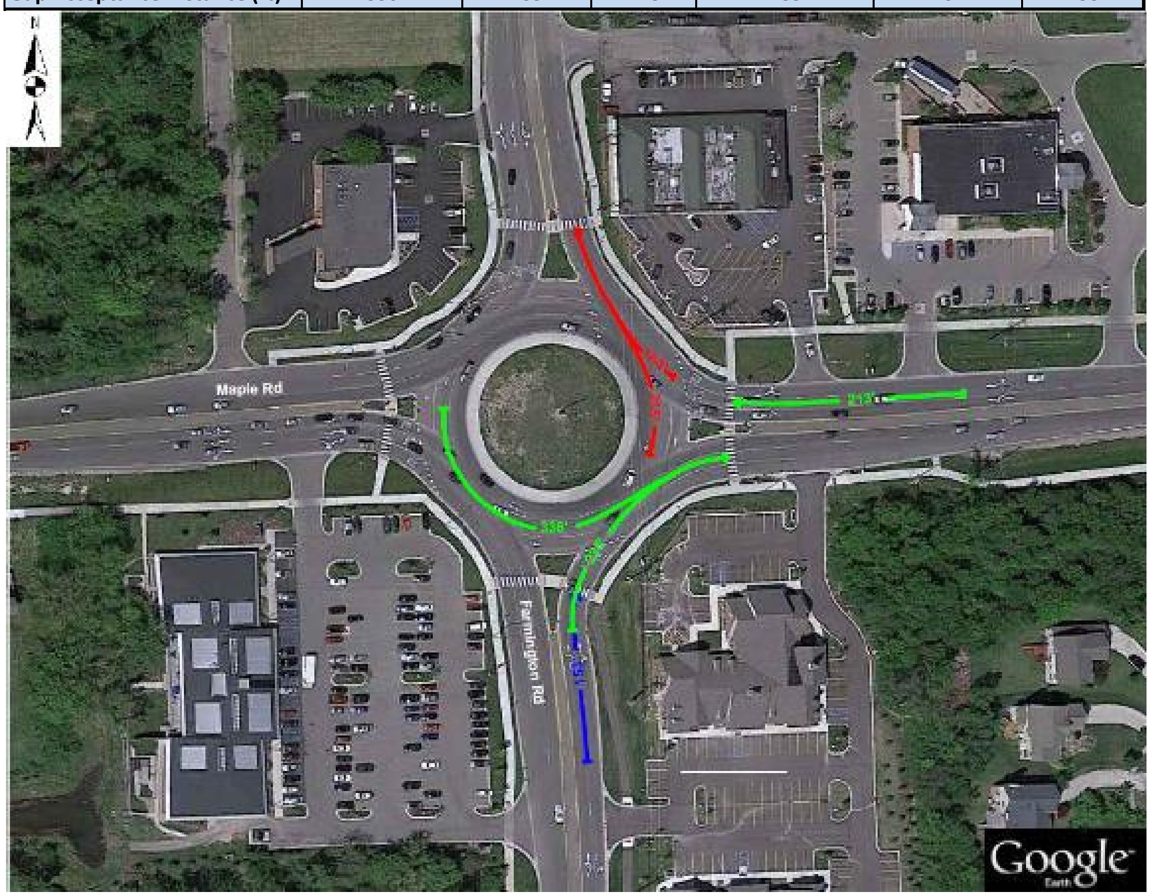
Cherrywood and Greenbelt Metro, Greenbelt MD							
Approach Leg: West Exit							
ICD (ft)	R1	R2	R3	R4	R5	d12	d23
96	67	40	97	40	86	105	155
	V,Radius	decel	accel	Field RCW	Min		
V1	17	25			17		
V2 (Sc)	14	31			14		
V3	19			16.5	17		
V4	14	31			14		
V5	18				17		
T & L	15						
R	17						
Approach Leg: West Entry							
ICD (ft)	R1	R2	R3	R4	R5	d12	d23
251	150	104				105	
	V,Radius	decel	accel	Field RCW	Min		
V1	23	29		17.3	17		
V2 (Sc)	20						
T	17.3						

11.7 Sight Distance Example Application

This appendix provides all the final calculations from the "Approach 3" method, and aerial views of all the study sites where calculated sight distance paths were calculated.

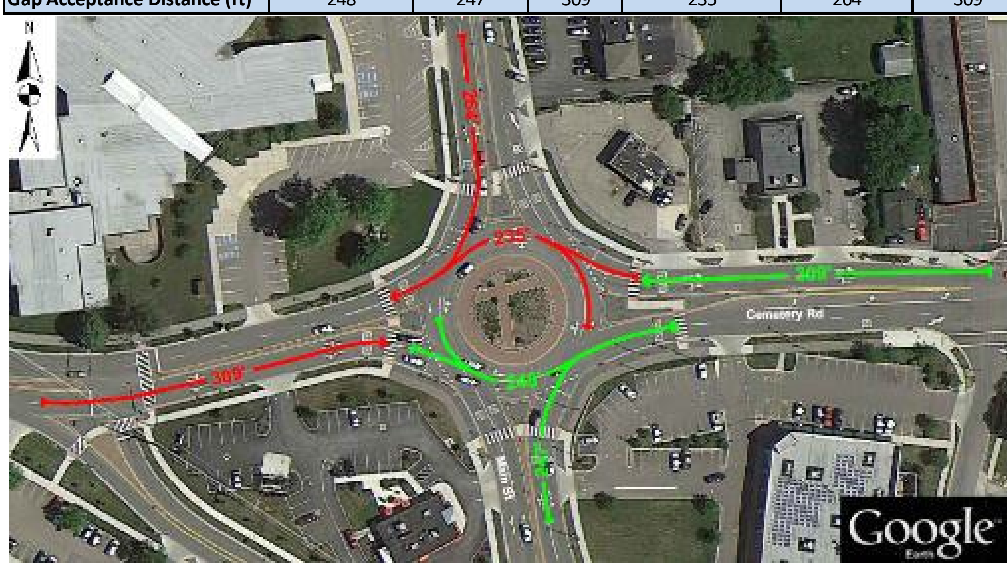
ROUNDABOUT CROSSING SIGHT DISTANCE RESULTS

Maple Rd and Farmington Rd., Novi, MI						
	East Exit (L & T)	East Exit (R)	East Entry	North Exit (L & T)	North Exit (R)	South Entry
R1	118	-	184	99	-	150
R2 & R4	104	-	104	104	-	104
R3	122	-	-	113	-	-
R5	-	166	-	-	105	-
Reaction Time (sec)	2	2	2	2	2	2
Crossing Width (ft)	36	36	32	23	23	21
Vehicle Speed (mph)	19	13	13	19	13	13
Gap Acceptance Distance (ft)	336	235	213	235	164	153

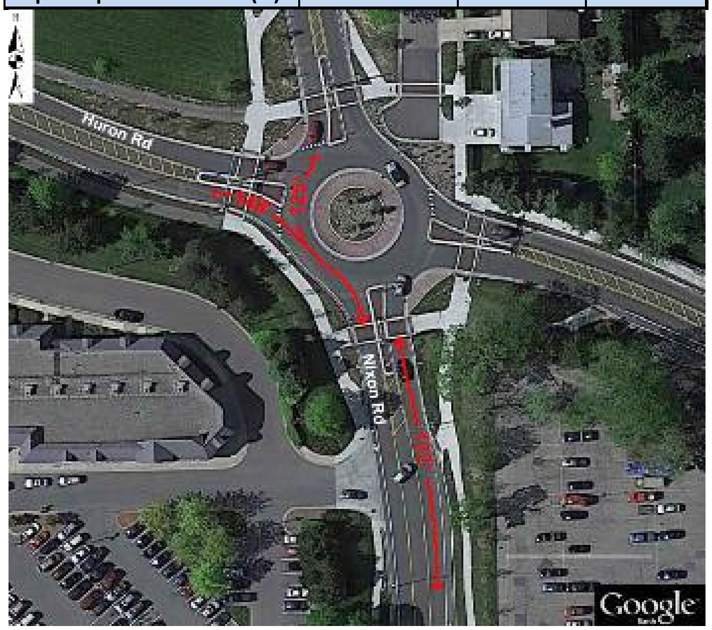


Cherrywood and Greenbelt Metro, Greenbelt MD			
	Westt Exit (L & T)	West Exit (R)	West Entry
R1	67	-	150
R2 & R4	40	-	104
R3	97	-	-
R5	-	86	-
Reaction Time (sec)	2	2	2
Crossing Width (ft)	14	14	14
Vehicle Speed (mph)	15	17	17
Gap Acceptance Distance (ft)	133	146	153

Cemetery Rd and Main St., Hilliard OH						
	East Exit (L & T)	East Exit (R)	East Entry	West Exit (L & T)	West Exit (R)	West Entry
R1	142	-	142	150	-	142
R2 & R4	66	-	66	66	-	66
R3	223	-	-	99	-	-
R5	-	110	-	-	110	-
Reaction Time (sec)	2	2	2	2	2	2
Crossing Width (ft)	22	22	26	24	24	26
Vehicle Speed (mph)	20	20	22	18	20	22
Gap Acceptance Distance (ft)	248	247	309	235	264	309



Nixon Rd and Huron Rd., Ann Arbor, MI			
	East Exit (L & T)	East Exit (R)	South Entry
R1	67	-	130
R2 & R4	43	-	43
R3	74	-	-
R5	-	87	-
Reaction Time (sec)	2	2	2
Crossing Width (ft)	12	12	12
Vehicle Speed (mph)	16	19	22
Gap Acceptance Distance (ft)	125	148	172



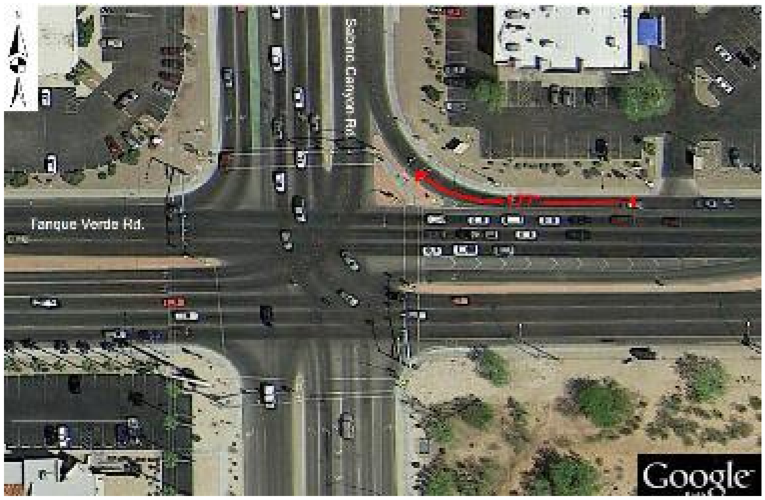
E Ellsworth Rd and State Rd., Ann Arbor, MI			
	West Exit (L & T)	West Exit (R)	West Entry
R1	140	-	184
R2 & R4	69	-	104
R3	223	-	-
R5	-	67	-
Reaction Time (sec)	2	2	2
Crossing Width (ft)	25	25	26
Vehicle Speed (mph)	21	17	25
Gap Acceptance Distance (ft)	277	226	341

Old Apex Rd. and W. Chatham St., Cary, NC			
	Westt Exit (L & T)	West Exit (R)	West Entry
R1	61	-	221
R2 & R4	48	-	48
R3	59	-	-
R5	-	0	-
Reaction Time (sec)	2	2	2
Crossing Width (ft)	11	11	13
Vehicle Speed (mph)	16	0	24
Gap Acceptance Distance (ft)	118	0	205

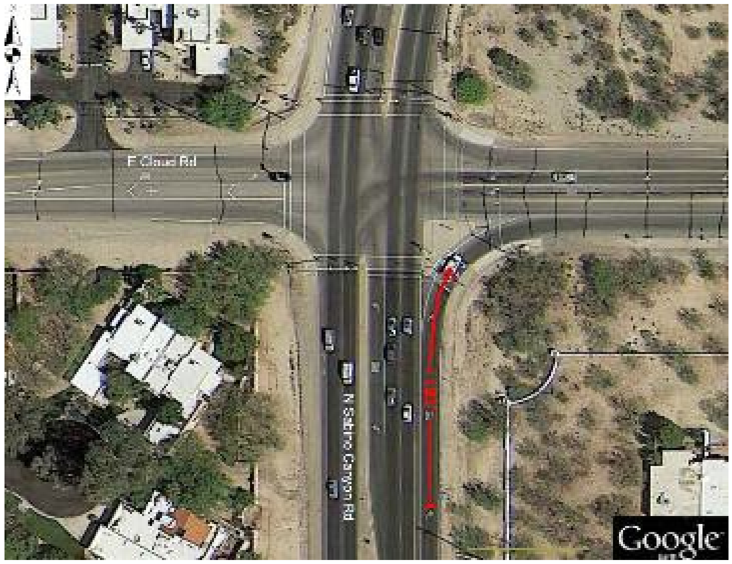
CHANNELIZED TURN LANES CROSSING SIGHT DISTANCE RESULTS

Grant Rd. and Oracle Rd., Tuscan AZ		
Approach	**SW**	**NE**
Radius of Curve (ft)	179	176
Reaction Time (sec)	2	2
Crossing Width (ft)	14.5	20
Vehicle Speed (mph)	20	21
Gap Acceptance Distance (ft)	177	237

Sabino Canyon & Tanque Verde Rd., Tuscan, AZ	
Approach	**NE**
Radius of Curve (ft)	176
Reaction Time (sec)	2
Crossing Width (ft)	14
Vehicle Speed (mph)	20
Gap Acceptance Distance (ft)	177



Sabino Canyon Rd. and Cloud Rd., Tuscan, AZ	
Approach	**SE**
Radius of Curve (ft)	89
Reaction Time (sec)	2
Crossing Width (ft)	17.5
Vehicle Speed (mph)	19
Gap Acceptance Distance (ft)	193

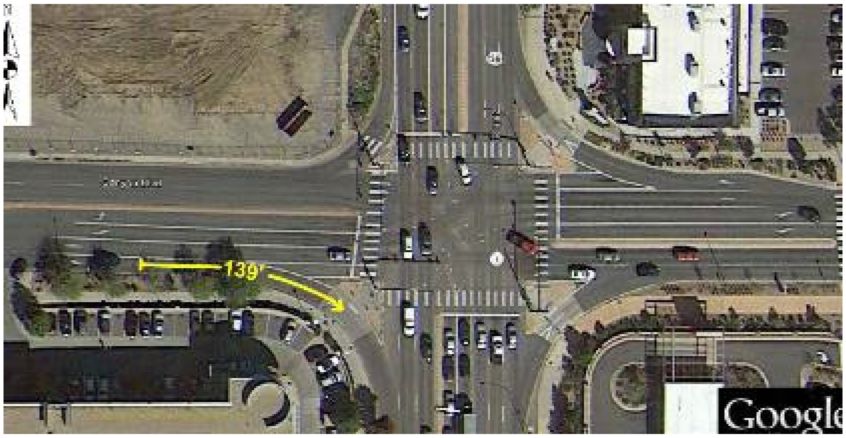


E. River Rd. and First Ave. (South Approach)	
Approach	**SE**
Radius of Curve (ft)	67
Reaction Time (sec)	2
Crossing Width (ft)	20
Vehicle Speed (mph)	17
Gap Acceptance Distance (ft)	191

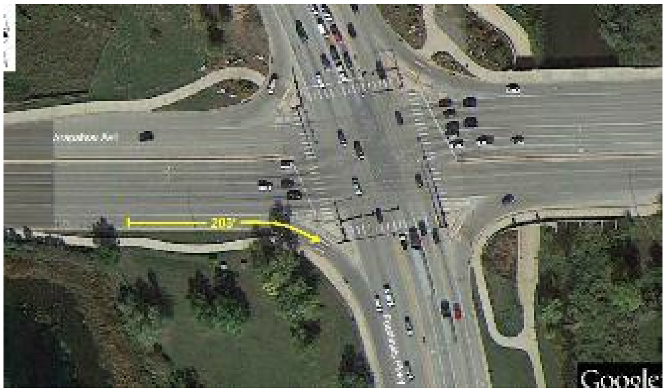
Wilmot Rd. and Speedway Blvd. (North Approach)	
Approach	NW
Radius of Curve (ft)	87
Reaction Time (sec)	2
Crossing Width (ft)	20
Vehicle Speed (mph)	19
Gap Acceptance Distance (ft)	210

28th St. and Pearl St., Boulder CO		
Approach	NW	NE
Radius of Curve (ft)	179	176
Reaction Time (sec)	2	2
Crossing Width (ft)	15	17
Vehicle Speed (mph)	14	20
Gap Acceptance Distance (ft)	129	203

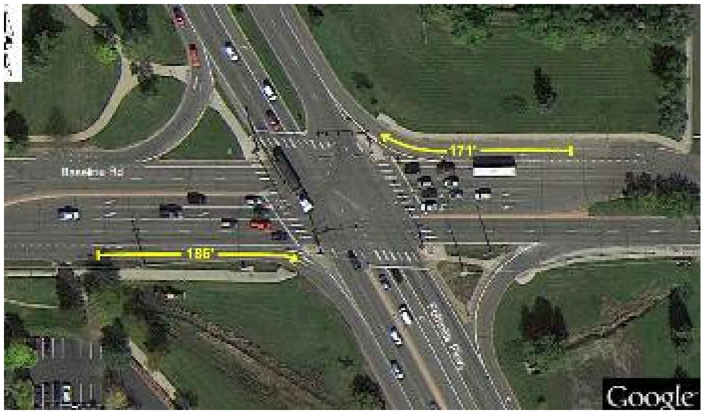
28th St. and Canyon Blvd., Boulder CO	
Approach	**SW**
Radius of Curve (ft)	115
Reaction Time (sec)	2
Crossing Width (ft)	15
Vehicle Speed (mph)	15
Gap Acceptance Distance (ft)	139



Foothills Pkwy. and Arapahoe Ave., Boulder CO	
Approach	**SE**
Radius of Curve (ft)	155
Reaction Time (sec)	2
Crossing Width (ft)	16
Vehicle Speed (mph)	21
Gap Acceptance Distance (ft)	203

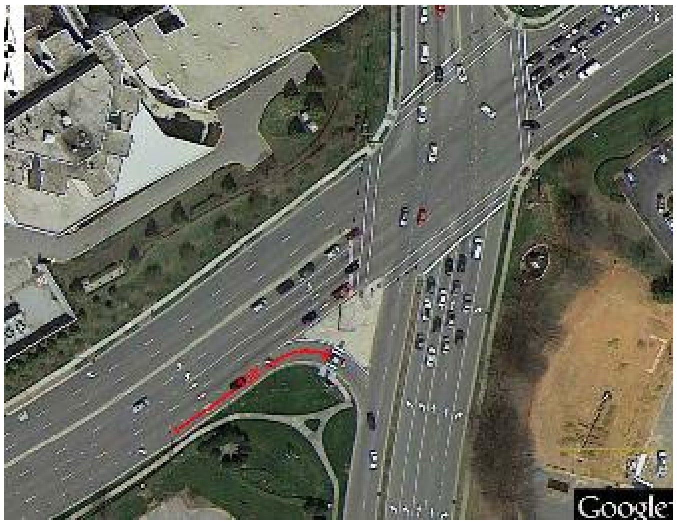


Foothills Pkwy. and Baseline Rd., Boulder CO		
Approach	SW	NE
Radius of Curve (ft)	179	176
Reaction Time (sec)	2	2
Crossing Width (ft)	14	16
Vehicle Speed (mph)	19	19
Gap Acceptance Distance (ft)	171	186



Kenilworth Ave, and E. West Hwy., Greenbelt MD	
Approach	NW
Radius of Curve (ft)	96
Reaction Time (sec)	2
Crossing Width (ft)	14
Vehicle Speed (mph)	19
Gap Acceptance Distance (ft)	170

Kildaire Farm Rd. and Tryon Rd., Cary NC	
Approach	**SW**
Radius of Curve (ft)	50
Reaction Time (sec)	2
Crossing Width (ft)	18
Vehicle Speed (mph)	15
Gap Acceptance Distance (ft)	158



12 APPENDIX E: SITE PHOTO LOGS

This appendix shows photo logs of all sites studied during this research. The appendix is organized by site.

12.1 Tucson, AZ Photo Log

12.1.1 Southwest Corner of Grant Road and Oracle Road

Figure 12-1: Drivers' view

a) Stop for pedestrians in crosswalk sign (not MUTCD standard, designed and used in Tucson) before crosswalk on both sides of CTL, sign enlarged at right.

b) No sign or marking indicating raised crosswalk (markings at this intersection are not complete).

c) Yield sign just past crosswalk, before yield point for Oracle Road.

d) Business sign restricts driver's view of pedestrian approaching crosswalk from south (right) around corner.

e) Island design and CTL design is relatively small, with relatively small turn radius.

f) Lane width is relatively narrow.

Figure 12-2: Pedestrian's view

Sidewalk landscaping ends before crosswalk area, when sidewalk is basically aligned with Grant Road traffic. Person who is blind who doesn't realize it's a CTL may cross from that point when contacting curb rather than continuing around corner to the crosswalk.

Figure 12-3: Raised crosswalk

a) Views of raised crosswalk construction and slope for vehicles, seems to be 3/72 transition slope or 1:24, basically very gentle for drivers.

b) Note stop line upstream of crosswalk.

Figure 12-4: Approach from south on sidewalk along Oracle (downstream street)

a) Landscaping that is on both sides of sidewalk when approaching is discontinued on the street side before the crosswalk. A person who is blind and unfamiliar with fact there is CTL at this location is likely to cross straight ahead when contacting curb rather than continuing around corner to the crosswalk. Driver will be looking left at that point.

b) Landscaping on left of sidewalk continues around corner to sign.

Figure 12-5: Curb ramp

Parallel ramp with cast iron detectable warning surface (truncated domes). At a parallel ramp, the whole sidewalk slopes down to a level landing. At this location, pedestrians need to turn at the bottom of the ramp to align for the crosswalk. Because of the raised crosswalk, the slope is less steep than at some locations, very subtle. Most participants seemed to use the slope as a cue, then the DW, curb line and traffic moving by them as an alignment cue. Parallel ramps typically have a raised curb area at the back of the ramp, which might be used for alignment in some cases.

Figure 12-6: Crosswalk view from the back of the ramp

Detectable warning surface is wider at island than at curb, very low curb on each side of DW on curb side within crosswalk.

Figure 12-7: Pedestrian path on island

Pedestrian path is paved, with gravel landscaping of the rest of the island. Benches on the island are used by pedestrians on a regular basis.

Figure 12-8: Returned curb on edge of ramp

Returned curb on edge of ramp at crosswalk may provide an alignment cue for pedestrians who are blind if aligned with crosswalk direction. Obviously not helpful for that if not aligned with direction of crosswalk.

Figure 12-9: Pushbutton alignment

a) On island, face of the pushbutton is aligned with crosswalk for the major street crossings, as is returned curb and edge of landscaping. Provides helpful cues for pedestrians who are blind.

b) Pushbutton placement is less consistent. Pushbutton location is at edge of landscaping and relatively easy to find. However, one of the buttons is not consistent with MUTCD guidance that pushbuttons be located in line with the crosswalk line furthest from the center of the intersection.

12.1.2 NE Corner of Grant Road and Oracle Road

Figure 12-10: Driver view of approach

a) Controller boxes in landscape strip may block driver's view of approaching pedestrian.

b) Same signs as on SW corner (stop for pedestrians in crosswalk before crosswalk, yield sign just past raised crosswalk).

c) Raised crosswalk with no sign or markings of raised crosswalk.

d) Wide lane, longer crossing for pedestrian than the CTL on the SW corner.

Figure 12-11: Driver view of pedestrian at crosswalk

Pedestrian standing at crosswalk was visible to approaching drivers, and sighted pedestrians could see drivers once they were at the crosswalk.

Figure 12-12: Pedestrian view of approach to crossing, along Grant

a) Landscaping along street side except at crosswalk can provide some guidance to crosswalk and provides separation from street, easier and more comfortable to trail with a cane than trailing the curb line.

b) Level sidewalk going around corner may make it more likely that a person who is blind will miss detecting the crosswalk and intersection altogether, if aware that it's a CTL and not looking for the ramp by trailing the edge of the sidewalk (may be particularly an issue for dog guide users).

Figure 12-13: Pedestrian approach along Oracle (from downstream end)

a) Landscaping keeps blind pedestrians from crossing at the wrong location.

b) Paved parking lot on side away from street may result in disorientation.

Figure 12-14: Lighting on the sidewalk

a) Lighting was provided over sidewalk, but no extra lighting at the crosswalk [we didn't look at it at night].

Figure 12-15: Pedestrian's view of approaching vehicles in CTL

Controller and other boxes on the side made some possibly confusing sound reflections of approaching and waiting vehicles (noted by O&M specialist), although no blind pedestrians commented on it, nor were there any decisions that were noticeably affected by that.

Figure 12-16: Wide perpendicular ramp from curb to island

a) Landscaping on each side of ramp, but outside the marked crosswalk. Because of landscaping, returned curbs could have been used on this ramp too and might provide alignment cues to pedestrians who are blind.

b) Detectable warnings at base of ramp at edge street.

c) Relatively low slope due to raised crosswalk.

d) Longer crossing for pedestrians than CTL crossing on SW corner.

e) Note stop line for drivers upstream of crosswalk.

Figure 12-17: Edge of landscaping not aligned with edge of crosswalk or with crosswalk direction

A blind pedestrian who lines up with it will end up outside the crosswalk.

Figure 12-18: Island pedestrian paths

Very similar to island on SW corner (see descriptions at Figure 12-7, Figure 12-8 & Figure 12-9).

12.1.3 Speedway Boulevard & Wilmot Road

Figure 12-19: Approach to channelized turn lane driver and pedestrian view

a) Deceleration lane

b) Stop sign on both sides of crosswalk (on curb and on island); stop sign on island visible to approaching driver.

c) Reflectors on poles on end of island, crash/visibility problem there?

d) Narrow sidewalk.

e) Landscaping between street and sidewalk.

f) Landscaping on back side of sidewalk and low wall.

g) No pedestrian crossing sign, although crosswalk is marked; crosswalk not visible to drivers until they start to turn.

Figure 12-20: Crossing view from upstream (on left) and downstream (on right)

a) Location of both stop signs visible.

b) Crosswalk marked, with stop line upstream of crosswalk.

c) Landscaping on both sides of sidewalk.

d) Perpendicular curb ramp slopes toward crosswalk, with landing behind ramp and main sidewalk path.

Figure 12-21: View of crosswalk

a) Paved area at ramp, including the ramp flare, is wider than the crosswalk. Some blind pedestrians stated that they tried to cross from the curb, not from the ramp, and moved onto the flare to begin their crossings.

b) No detectable warnings (truncated domes) installed at base of ramp.

Figure 12-22: View of island

a) Island is all paved with curb ramps to crosswalks; orientation problems for blind pedestrians; some trailed curb with their cane to find ramp and crossing point then got turned around when looking for pushbuttons.

b) Pushbuttons on poles near center of island.

c) Additional poles and reflective signs on island.

d) Audible signal for main crossings of Speedway and Wilmot.

Figure 12-23: Pushbuttons on island

a) Pushbuttons are in line with each crosswalk but located more than 10 back from the edge of the street.

b) No pushbutton locator tone so blind participants had to search around for them.

c) No tactile arrow on pushbutton; some blind participants pushed the wrong button for their crossing.

d) Audible signal mounted on top of pedestrian signal pole above the pushbuttons.

Figure 12-24: View of crossing across Wilmot

a) Wide crossing.

b) Curb ramp without detectable warnings angled to left of crosswalk.

c) Pushbutton close to crosswalk, but no pushbutton locator tone.

Figure 12-25: Reflectors on island

Signs on the island have sharp protruding edges, hazardous for pedestrians who are blind.

12.1.4 E. Tanque Verde Road and Sabino Canyon Road

Figure 12-26: Approach view of CTL, sidewalk and crosswalk

a) Right turn only sign (deceleration lane).

b) Yield sign on each end of crosswalk).

c) Lane designation sign on island.

d) Fairly wide lane and large radius on CTL.

e) Sidewalk is wide (6 feet) and at back of curb with no landscape separation between street and sidewalk.

f) There is landscaping with gravel on side away from street.

Figure 12-27: Yield signs at CTL

a) Yield signs at crosswalk with shark's teeth marking about 4 feet in advance.

b) Yield sign a merge point with Sabino Canyon Road.

Figure 12-28: Combo curb ramp

a) Curb ramp is combo parallel type, sidewalk slopes down approximately 3 inches, and a section of ramp is perpendicular to the street.

b) Detectable warnings are installed on the perpendicular section.

c) Raised curb at back of sidewalk is typical of a parallel ramp.

Figure 12-29: Paths on island

a) Cut-through pedestrian paths well-defined.

b) Crosswalk, and ramp on curb side, is wider than cut-through area. [One of our pedestrians ended up outside the cut-through when crossing and stepped up onto the paved surface. She thought the cut-through was the curb of the street when she came to it.]

c) Detectable warning surface at edge of street at CTL, and each crossing.

d) Island paved outside of cut-through areas.

e) Pushbuttons on raised section beside street and edge of cut-through path.

Figure 12-30: Pushbutton location

a) Pushbutton is on side furthest from the center of the intersection for Sabino Canyon crossing (as per MUTCD guidance).

b) Pushbutton for crossing Tanque Verde, photo on left, is on side closest to the intersection.

c) Cut-through gathers trash and gravel along the edges, as can be seen in these photos, particularly one on left.

Figure 12-31: Vehicular downstream lane merge

a) There's a lane that could be used as acceleration lane, but is really decel lane for shopping center entrance. Most vehicles did merge directly into the main travel lanes.

12.2 Boulder, CO Photo Log

12.2.1 Southwest Corner of Baseline Road and Foothills Parkway

Figure 12-32: Drivers' view on approach (SW corner)

a) Yield sign at crosswalk.

b) Placard below yield sign: bicycle symbol, pedestrian symbol, two-headed arrow and 2-WAY CROSSING (photo at right).

c) Bicycle lane between right turn lane and through lanes.

d) Controller might restrict driver's view of pedestrian.

e) Sound strips in deceleration lane.

f) Lane width of CTL relatively narrow.

Figure 12-33: Shared use path joins sidewalk

a) Path from right, sign: MULTIUSE PATH USE CROSSWALK THROUGH INTERSECTION.

b) Bicycle ramp from street to trail/path.

Figure 12-34: Pedestrian's view on approach

a) Wide shared use path.

b) Landscape buffer strip between sidewalk and roadway,

c) Also grass on side away from street.

d) Sidewalk turns toward crosswalk.

e) VEHICLE CROSSING sign before crosswalk.

Figure 12-35: Closer view of crosswalk

a) Ramp and curb line not aligned with crosswalk

b) Ramp slope and detectable warning alignment may direct pedestrian past end of island (to left), particularly if they have been trailing sidewalk on the side closest to street (common technique observed with several participants in research); arrow approximates their path, sometimes hitting the sound strip and going around it.

c) Continental pavement marking on crosswalk somewhat worn.

d) Water puddle at base of ramp (may have affected alignment of some participants who moved to side to avoid it).

e) Sound strip closest to crosswalk visible at left.

Figure 12-36: Sound strips

Temporary strips did move over course of day (not originally intended for this purpose and amount of traffic). Note white temporary chalk marks. Strips were moved back in position before each participant's trials.

Figure 12-37: Sound strips in deceleration lane

Six strips installed across lane, spaced 30 feet apart (Road Quake temporary rumble strips).

Figure 12-38: Island

a) Island was quite small, particularly considering the amount of bicycle traffic.

b) Detectable warnings on ramps; slope and DW seemed to help participants find ramp locations to cross main street sections.

c) Two pushbuttons on signal pole.

Figure 12-39: Aligning to cross Baseline Road from island

a) Ramp sloped toward center of intersection.

b) Detectable warnings, ramp slope, and island curb line, as well as perpendicular traffic, if used for alignment, aimed participant toward the center of the intersection; parallel traffic was heavy and provided a good alignment cue if participants waited for it.

c) Face of pushbutton relatively well aligned with crosswalk direction.

d) Pushbuttons had visual arrows but no tactile or audible features.

Figure 12-40: Aligning to cross Foothills Parkway from island

a) Ramp sloped toward center of intersection.

b) Detectable warnings, ramp slope, and island curb line, as well as perpendicular traffic, if used for alignment, aimed participant toward the center of the intersection; parallel traffic was heavy and provided a good alignment cue if participants waited for it.

c) Face of pushbutton relatively well aligned with crosswalk direction.

d) Pushbuttons had visual arrows but no tactile or audible features.

Figure 12-41: Pedestrian's view of approaching vehicles

Pedestrian's view of approaching vehicles was partially blocked by the position of the controller. Did not seem to block sound, so not an issue for blind pedestrians, but noticeable to orientation and mobility specialist visually monitoring vehicle approaches and safety.

12.2.2 Northeast Corner of Foothills Parkway and Baseline Road

Figure 12-42: Drivers' view on approach (NE corner)

a) Deceleration lane.

b) Yield sign at crosswalk.

c) Bicycle lane between deceleration lane and through lanes.

Figure 12-43: Pedestrian view on approach

a) Sidewalk at back of curb.

b) Grass growing in crack between sidewalk and curb.

c) Crosswalk around corner just past the yield sign (NOT where pedestrian is standing in photo).

Figure 12-44: View of crosswalk and island

a) Pavement marking worn and almost non-existent from curb to island.

b) Parallel curb ramp (sidewalk slopes down to level landing area at crossing).

c) Sidewalk ends at crosswalk.

d) Detectable warning surfaces have gathered debris and dirt.

e) Pushbuttons on signal pole on island.

f) Raised curb on left side of crosswalk to cross Foothills Parkway (not present on other ramps). Rough (bricklike) surface of areas outside of ramps and crosswalks did not deter blind participants from traveling on or lining up on that surface.

Figure 12-45: Narrow island crossing

a) Island was quite narrow, disconcerting to some participants to be so close to heavy traffic.

b) Detectable warning surface near Foothills Parkway was depressed, rather than level with the crossing area.

Figure 12-46: Pushbutton to cross Foothills Parkway (road to right in photo)

a) Quite a distance from the crosswalk. (Photographer is standing at crosswalk.)

b) No audible or tactile features.

Figure 12-47: Aligning to cross Foothills Parkway

a) Pushbutton aligned with crossing but not possible to reach it from crosswalk area.

b) Curb between detectable warning surface and pushbutton.

Figure 12-48: Aligning to cross Baseline Road

a) Ramp, detectable warnings and curb line angled toward center of intersection; may direct someone toward traffic lanes.

b) Pushbutton on signal pole near crosswalk, but face of pushbutton and sign are aligned toward the intersection rather than in line with the crosswalk.

12.2.3 Southwest Corner of Foothills Parkway and Arapahoe Ave

Figure 12-49: Driver's approach to CTL along Arapahoe

a) Wide deceleration lane.

b) Sign: RIGHT LANE MUST TURN RIGHT, BUSES EXCEPTED.

d) Sign: SLOW RAISED X-WALK.

d) Yield sign at crosswalk.

Figure 12-50: Pedestrian's view of approach to CTL

a) Wide sidewalk/shared use path.

b) Landscaping on both sides of path, ends on street side before crosswalk.

c) Yield sign at crosswalk.

d) Bollard before crosswalk.

Figure 12-51: Pedestrian view from downstream sidewalk

a) Wide sidewalk at back of curb.

b) Raised crosswalk at sidewalk level.

Figure 12-52: Crosswalk view

a) Raised crosswalk.

b) Wide crosswalk with continental stripes.

c) Detectable warnings at edge of street and for full width of crosswalk, but do not extend the full width of area of the sidewalk that is level with the street. (Sidewalk is level with the street for almost a foot past marked edge of crosswalk.)

d) Island is large, paved area with a wide curb ramp to each street.

e) Returned curbs on edge of each ramp.

Figure 12-53: View of crosswalk across Foothills Parkway

a) Ramp with returned curbs on side.

b) Aligned with crosswalk direction.

c) Two pushbuttons on one pole between ramps for the two streets.

d) Detectable warning at curb edge for full width of ramp.

Figure 12-54: View of crosswalk across Arapahoe

a) Same basic setup as crosswalk across Foothills Parkway.

12.2.4 28th and Pearl, Northeast Corner CTL

Figure 12-55: Drivers view on approach to 28th Street on Pearl

a) Right turn decel lane.

b) RIGHT LANE MUST TURN RIGHT sign, partially obscured by trees.

c) Eight turn arrow lane markings.

d) Bicycle lane to left of right turn lane.

e) High curb on street.

Figure 12-56: Driver's view of crosswalk (NE Corner 28th and Pearl)

a) Marked crosswalk, not raised.

b) Bollards on the curb and island.

c) Yield sign just before crosswalk on right.

Figure 12-57: Pedestrian's view on approach

a) Sidewalk widens at corner.

b) Landscaping ends before crosswalk.

c) Bollards on each side of crosswalk and other locations on curve.

d) Perpendicular ramp at crosswalk.

Figure 12-58: Pedestrian approach from downstream street

a) Wide sidewalk with landscaping between street and sidewalk that ends before crosswalk.

b) Crosswalk around curve of CTL.

Figure 12-59: Gap between SW and curb

a) Dave commented that the 1 to 2 inch gap confused some participants on approach.

Figure 12-60: View of downstream merge area

a) Pavement markings in shade, BIKE BUS ONLY. b) Sign on left hidden behind trees in photo on right.

6

Figure 12-61: View of crosswalk and island

a) Bollards on each side of crosswalk.

b) Wide crosswalk with continental markings.

c) Detectable warnings, ramp slope and gutter in line with crosswalk direction.

d) Island raised and paved with somewhat rough textured material outside of concrete path.

e) Bollards on each side of crosswalk on island.

f) Pushbuttons on one signal pole between crosswalks.

Figure 12-62: Crosswalk across 28th Street from island

a) Crosswalk slope, detectable warning and gutter aim to right of crosswalk direction toward median.

b) Pushbutton (non-audible) on pole to intersection side of crosswalk.

c) No level landing at pushbutton.

Figure 12-63: Crosswalk across Pearl Street from island

a) Wide crossing, 7 lanes.

b) Gutter, detectable warning, and ramp aligned slightly left of crosswalk direction.

c) Pushbutton to right of crosswalk (on parallel street side).

d) No level landing at pushbuttons.

Figure 12-64: View of island surface

a) Slight color difference of area outside walking path.

b) No discernible texture difference for blind participants.

12.2.5 28th and Pearl, Northwest Corner CTL

Figure 12-65: Driver's view on approach, northwest corner

a) Decel lane.

b) Tree-lined road.

Figure 12-66: Closer view of crosswalk

a) Right turn arrow.

b) Lane continues straight with bus only markings.

c) SLOW RAISED CROSSWALK sign.

d) Yield sign at crosswalk.

e) Bollards on each side of crosswalk on curb and island.

Figure 12-67: Pedestrian approach to crosswalk

a) Wide sidewalk.

b) Sidewalk at back of curb.

c) Yield sign just before crosswalk.

d) Raised crosswalk.

e) Bollards at each side of crosswalk and in middle of crosswalk area.

f) Entrance to buildings at right.

Figure 12-68: Photo showing slope, for vehicles, of raised crosswalk.

Figure 12-69: View across crosswalk and island

a) Wide crosswalk.

b) Somewhat faded marking.s

c) Detectable warnings on both ends of crosswalk.

d) Bollards at each side and in center of crosswalk area.

e) Relatively large island, all paved with curb ramps to signalized sections of crossing.s

f) Two pushbutton on one pole on island.

Figure 12-70: Crosswalk across Pearl Street on west side

a) Pushbuttons beside curb ramp (no level landing).

b) Detectable warning, gutter and slope of ramp aim left of crosswalk.

Figure 12-71: Crosswalk across 28th Street

a) Pushbutton on left, street side, of ramp.

b) Face of button aligned with crosswalk directions.

c) Detectable warning, ramp slope, and gutter all aligned to right of crosswalk direction.

12.2.6 28th Street and Canyon Boulevard

Figure 12-72: Driver's view of approach to crosswalk

a) Deceleration lane.

b) RIGHT LANE MUST TURN RIGHT, BUSES EXCEPTED on sign hidden by trees.

c) Right turn arrow pavement markings.

Figure 12-73: Driver's view of crosswalk when approaching

a) Raised crosswalk markings.

b) Raised crosswalk warning sign, obscured by trees.

c) Pedestrian waiting on curb side hidden by bushes, with restricted line of sight.

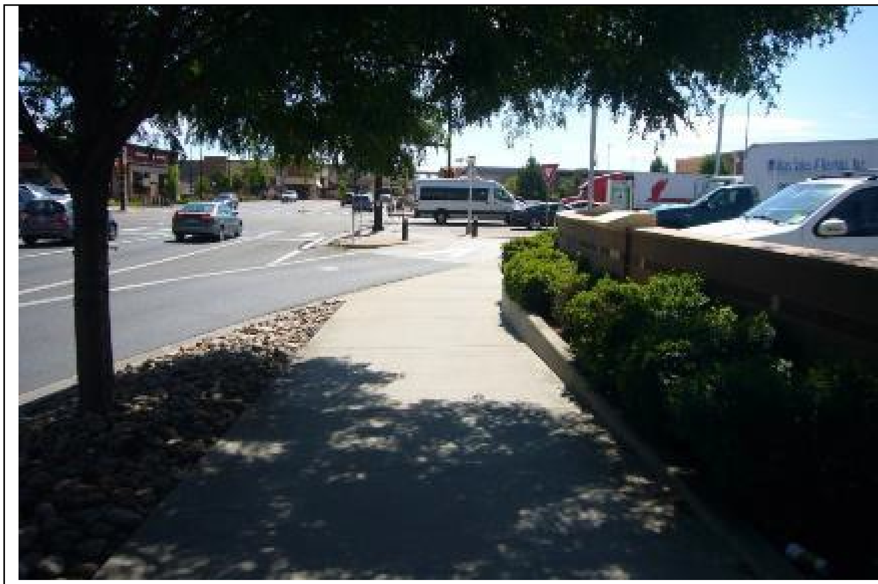


Figure 12-74: Pedestrian approach to crosswalk along Pearl

a) Wide sidewalk.

b) Shaded by trees.

c) Landscaping and wall on side away from stree.t

d) Landscaping on street side until about 25 feet before crosswalk, then sidewalk at back of curb.

Figure 12-75: Pedestrian and driver view from close to crosswalk

a) Yield sign just before crosswalk on curb side.

b) Bollards at each edge of raised crosswalk.

c) Concrete raised crosswalk.

Figure 12-76: View of crosswalk from downstream end of CTL

a) Wide sidewalk at back of curb.

Figure 12-77: Pedestrian view across crosswalk and island

a) Scoring on sidewalk at raised crosswalk.

b) No detectable warning at edge of street.

c) Worn, almost non-existent crosswalk markings.

d) Flat paved island, with curb ramps to each signalized crossing.

e) Bollards on each side of raised crosswalk.

Figure 12-78: Crosswalk across 28th Street

a) Island all paved.

b) Perpendicular curb ramp.

c) Two pushbuttons on pole near crosswalk (no level landing).

d) Detectable warning at base of curb ramp.

e) Marked crosswalk.

Figure 12-79: Crosswalk across Canyon Boulevard

a) Curb ramp aligned slightly left of crosswalk direction.

b) Marked crosswalk.

c) Pedestrian pushbutton on pole.

d) Detectable warning at base of curb ramp.

12.3 Hilliard, OH Photo Log

Figure 12-80: Approach from south (looking north)

There is another roundabout just south along Main Street. Photo shows view from just south of pedestrian crosswalk for Scioto Darby Road and Main Street roundabout, looking north on Main Street toward the Main Street/Cemetery Road roundabout.

Figure 12-81: Signs on approach from south

Extensive signage between the two closely spaced roundabouts. Highway guide signs, followed by lane control sign, then almost immediately followed by the pedestrian crosswalk on the south side of roundabout.

Figure 12-82: View of roundabout from south median, at north pedestrian crosswalk for Scioto Darby Road roundabout

Lane control pavement markings and sign are shown here.

Figure 12-83: Driveways close to roundabout

On all approaches, there were driveways quite close to the roundabout, just beyond the pedestrian crosswalk. Exits from driveways had stop signs and no left turn signs, as well as one way signs on the median, as shown in photo on right.

Figure 12-84: TO BOTH LANES IN ROUNDABOUT plaque added below YIELD sign on all approaches.

Figure 12-85: Red reflective sheeting was added on posts of some YIELD signs.

Figure 12-86: Rough "cobblestone" surface used to separate sidewalk and roadway

Dark cobblestones were used to separate the sidewalk from the roadway, beginning before each pedestrian crosswalk and continuing around the curve of the roundabout to the next crosswalk. As seen in photo, sidewalk and curb ramp were concrete and/or asphalt (some sidewalk areas). The cobblestone surface was relatively detectable under foot and under cane, but blind participants did not recognize it as a non-walking surface, so it didn't provide guidance (that might have been intended) without specific training. Inset on right shows size of cobblestones in comparison to foot.

Figure 12-87: Overhead school crossing flashers

Overhead school crossing flashers installed on north and east crosswalks. Flash from 7:00 – 7:40 am and 2:10 – 2:52 pm, Monday – Friday during school days for school arrival and departure. They do not operate in the summer months.

Figure 12-88: Yield signs and markings at crosswalk

a) Crosswalks were marked with continental style markings.

b) Had yield pavement markings before the crosswalk, and pedestrian crossing warning signs on curb side (W11-2 with a diagonal downward pointing arrow, W16-7P plaque).

c) In addition, there were in-crosswalk STATE LAW YIELD TO PEDESTRIANS IN CROSSWALK signs (R1-6), which were also installed on posts on the splitter islands.

Signs varied from crosswalk to crosswalk; pavement word markings YIELD were installed on all approaches; School crossing signs (rather than pedestrian crossing signs) were used at the east and north crosswalks, accompanied by overhead mounted flashers. Pedestrian crossing warning signs were used on the west and south crosswalks. All crosswalks had the in-crosswalk signs on the center lane line and post-mounted on the splitter.

Figure 12-89: R1-6 used as post mounted signs on splitter islands

Figure 12-90: Lane drop just past roundabout

There was a lane drop on east, and north exits of the roundabout. Sign, RIGHT LANE ENDS (W9-1), just beyond crosswalks followed by END SCHOOL ZONE and LANE ENDS (W4-2) sign and pavement markings.

Lots of signs right near crosswalk.

Figure 12-91: Crosswalk for exit set back from circulatory roadway (east crosswalk)

Crosswalk for exit is further from circulatory roadway than the entry crosswalk with zig-zag cut-through median. Is it better for pedestrians? Higher speeds at crosswalk?

Figure 12-92: Zig-zag cut-through of island

Island cut-through with zig-zag to guide to offset exit and entry crosswalks; detectable warnings at edge of streets, cut-through curbs aligned with direction of crosswalk; cut-through area is smooth concrete; rest of island is the dark cobblestone pavers; small solar-powered lights on splitter near crosswalk cut-through.

Figure 12-93: Island cut-through edge is aligned with crosswalk (photo at north crosswalk)

Figure 12-94: Ramp is generally aligned with crosswalk

(east crosswalk)

a) Slightly angled right due to rbt curvature at entry.

Figure 12-95: Narrow splitter islands on west and south approaches

Island on west and south legs were much narrower than north and east legs. Island was cut-through with detectable warnings installed. Curbs on island cut-through were generally aligned with the crosswalks.

Figure 12-96: View of roundabout when approaching from east

Roundabout sign, GMI signs, overhead flashers, pavement markings, etc.

Figure 12-97: Signs on east approach

Figure 12-98: Pavement markings within roundabout, and directional signs on splitter island

Figure 12-99: Flashers and markings in advance of crosswalk.

School flashers and extensive pavement marking, as well as signs (east and north approach).

Figure 12-100: Control box extended into crosswalk approach area at head height for pedestrians who are blind.

Although there is a steep flare on the ramp on that side of the pole, a blind individual approaching along the sidewalk (from left in photo) could turn by the pole and contact the box with the face! The installation could be hazardous and does not meet protruding objects requirements of the ADA (extends more than 4 inches from post).

Figure 12-101: North crosswalk exit lane crossing

North crosswalk also has pedestrian flashers, school crossing sign, and a lane drop shortly beyond the crosswalk (no LANE ENDS sign here).


Figure 12-102: Island decorative elements

A rather unusual planting arrangement has a section that almost looks like a sidewalk. This is just an architectural element rather than a sidewalk; may also be used by maintenance crews.

Figure 12-103: Sidewalk dip near crosswalk was confusing to some blind participants

The sidewalk sloped down and back up relatively steeply, just north of the crosswalk (north crosswalk, west end), which some blind participants mistook for a ramp to the crossing. More than one lined up, in line with the sidewalk, at the bottom of the dip and thought they were at the street edge. Under foot and with a cane, it seemed like the gutter at the edge of the street; it may be that the dip was related to water flow; not sure why it was there.

Figure 12-104: Zig-zag island at north crosswalk (used for wayfinding trials)

Figure 12-105: Roundabout sign on north and west approaches

a) Road widens to two lanes on approach, just past the school crosswalk north of the roundabout.

Figure 12-106: West crosswalk

a) Pedestrian crossing warning sign.

b) In-crosswalk sign.

c) Lane drop is around curve, but most drivers stay in left lane (probably because of lane drop).

Figure 12-107: Narrower island on west approach

Figure 12-108: Children crossing

12.4 Oakland County, MI Photo Log

Figure 12-109: South leg, directional sign on approach

Figure 12-110: Driver's view on approach

a) Yield ahead sig.n

b) Road widens to two lane.s

c) Pavement markings and sign with lane assignment.s

d) Pedestrian warning signs and RRFB’s at crosswalk (barely visible in this picture).

e) NO sign regarding raised crossing or speed hump.

Figure 12-111: Driver's view - closer to crosswalk.

a) Lane control assignment pavement markings and sign.

b) Pedestrian warning sign and RRFBs.

c) White triangular markings on edge of raised crosswalk visible (only notice of presence of raised crosswalk).

d) NOTE: Raised crosswalks only on south leg entry, east leg entry and exit, and north leg exit; drivers entering from west didn't encounter raised crosswalk until/unless they exited on east or north leg.

Figure 12-112: Driver's view of raised crosswalk from 100 feet back

a) Additional lane assignment markings, just before crosswalk.

b) Temporary raised crosswalk.

c) RRFBs at crosswalk.

d) Yield sign at entry, with one way placard on top.

e) Yellow and black chevrons on island.

Figure 12-113: Pedestrian view of approach

a) Grass landscaping on both sides of sidewalk/path at all locations around roundabout except at crosswalks.

b) RRFBs and pedestrian warning signs at crosswalk.

Figure 12-114: Grass landscaping on both sides of wide sidewalk

Figure 12-115: Different ramp configurations

Photo on left: south crosswalk, entry lanes:

a) Perpendicular ramp outside of sidewalk area.

b) Slopes to crosswalk.

c) Slope aligned slightly to left of crosswalk direction.

d) Raised crosswalk installed.

Photo on right: east crosswalk, exit lane side:

a) Parallel combo ramp.

b) Sidewalk slopes down to level landing at crosswalk location.

c) Small slope down to street level at detectable warning.

d) Raised crosswalk installed.

Figure 12-116: View of temporary speed humps installed as raised crosswalks

a) Triangular marking on edge of speed hump.
b) No crosswalk markings.
c) Rubber material.
d) Raised approximately 3 to 4 inches for vehicles.
e) Steep slope up from gutter for pedestrians is not ADA compliant.
(NOTE: this was installed temporarily forresearch.)

Figure 12-117: Pedestrian view of crosswalk: south crosswalk

a) Detectable warning at edge of street.

b) Ramp slope and DW line up slightly to left of direction of travel on the crosswalk.

c) Pushbutton on pole next to crosswalk.

d) RRFBs installed with crosswalk warning device (or audible information device) on pole with pushbutton locator tone and speech message, “The yellow lights are flashing” when button is pressed.

e) RRFBs flash for approximately 20 seconds.

f) Temporary speed hump material installed as raised crosswalk on entry lanes only.

Figure 12-118: RRFB mounted too low

RRFBs were mounted so the lower edge of the arrow sign was at head height for a 6-foot-tall person. One of the blind participants almost hit his head while reaching for the pushbutton. Signs and RRFB need to be raised so the bottom edge is above 7 feet.

Figure 12-119: Island, lining up to cross exit lanes; south crosswalk.

a) Gutter aligned perpendicular to crosswalk.

b) Cut-through concrete not aligned with crosswalk direction.

c) DW not in line with crosswalk.

d) RRFB and pushbutton on downstream side, more than 5 feet back from curb.

Figure 12-120: South crosswalk exit lane; used for wayfinding trials

a) Ramp, DW and gutter aligned to left of crosswalk direction.

b) No raised crosswalk.

c) Three-lane crossing.

Figure 12-121: Island, alignment of crossing for entry lanes, south crosswalk

a)DW and gutter aligned to left of crosswalk direction.

b) Raised crosswalk.

Figure 12-122: Crossing exit lanes, east crosswalk

a) Curb ramp aligned with crosswalk direction.

b) Pushbutton beside ramp with button aligned with direction of travel on crosswalk.

Figure 12-123: East crosswalk - merging traffic as road narrows from three lanes to one lane just past crosswalk

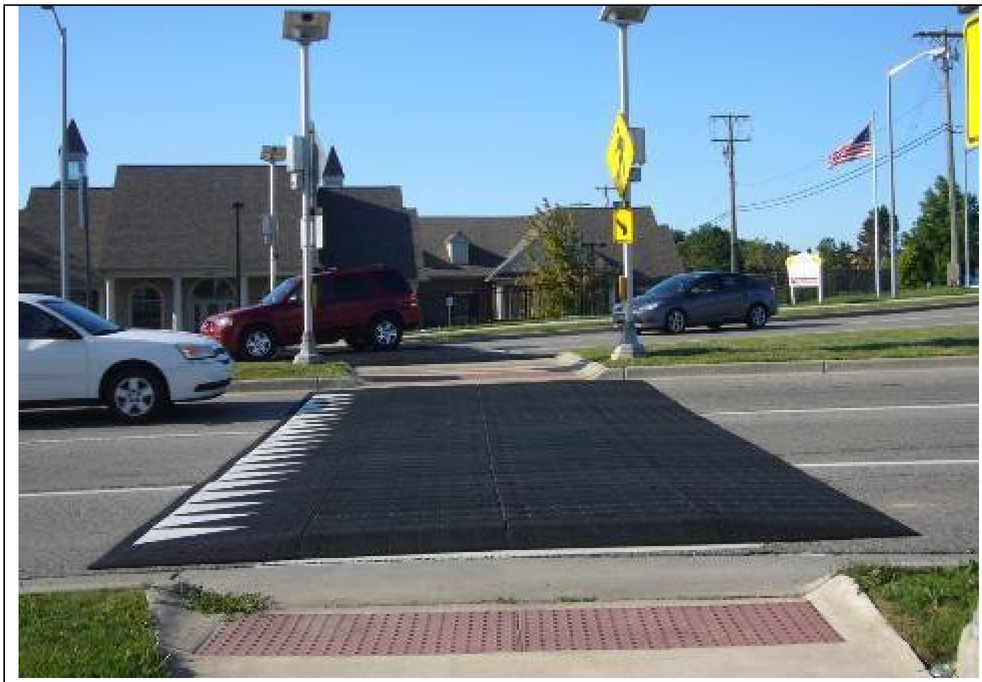


Figure 12-124: Pedestrian view of east crosswalk (looking north)

a) Three lane crossings.

b) Detectable warning at edge of street.

c) Raised crosswalk for entry and exit lanes.

d) Narrow splitter island with pushbuttons for RRFBs installed on downstream side for each crossing.

Figure 12-125: Signage and markings on approach from east

a) Lane assignment pavement

markings.

b) Informational sign.

c) Pedestrian crossing warning sign.

d) Yield ahead sign.

e) Lane assignment sign and pavement markings.

Figure 12-126: East leg – three-lane entry, closer view

Figure 12-127: Sidewalk on east leg, north side

On the north side of Maple Road, the sidewalk is over 20 feet from street approaching the intersection. It turns toward the roundabout at the crosswalk and continues with about a 4 foot landscape strip around the roundabout. Some wayfinding trials for this leg (crosswalk on left) began from a location near the lower edge of the photo.

Figure 12-128: View of east entry leg pedestrian crosswalk

a) Crosswalk aligned with gutter and detectable warning, slightly out of alignment with approach sidewalk.

b) RRFB and pushbutton for RRFB on downstream side of crosswalk.

c) Participants commented that the pushbutton locator tone on audible information device was hard to hear at this location.

Figure 12-129: View of raised crosswalk

a) Note steep rise on edge, somewhat of a tripping hazard for pedestrians.

b) May have thrown off alignment for some individuals.

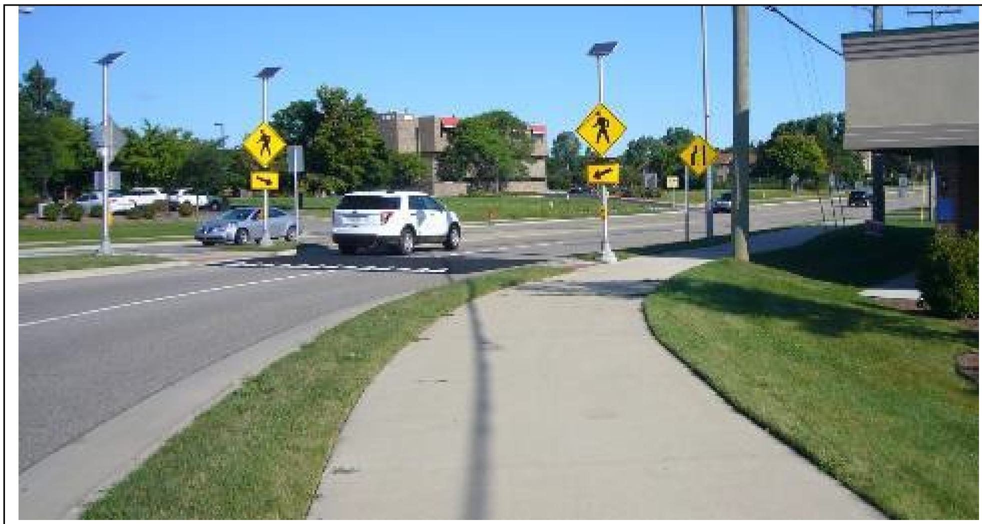


Figure 12-130: Pedestrian approach to north crosswalk

a) Landscaping on both sides of crosswalk.

b) Curb ramp outside of sidewalk area (had to trail grass to find it).

c) RRFB and audible information device with pushbutton locator tone beside crosswalk.

d) Raised crosswalk on exit lane.s

e) Pedestrian crossing warning sign at crosswalk.

Figure 12-131: View of North crosswalk

a) RRFBs, raised crosswalk.

b) Note lane drop just past crosswalk.

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Figure 12-132: Closeup view of audible information device

a) Speaker in device.

b) Message when pushed: “yellow lights are flashing.”

c) Message repeated.

d) Tactile arrow on device aligned with direction of crosswalk.

Figure 12-133: North crosswalk and island pedestrian view

a) Curb ramp and DW aligned slightly left of crosswalk direction.

b) Returned curb aligned very slightly to left.

c) Pushbutton on downstream side of crosswalk.

d) Island grass outside of cut-through area.

Figure 12-134: view of North crosswalk, from west, showing narrow splitter island

a) Not raised for entry lanes.

b) RRFB on opposite sides of crosswalk (downstream side).

Figure 12-135: View of west crosswalk

a) West crosswalk - RRFBs and audible information devices installed but no raised crosswalk.

Figure 12-136 Lane pavement markings within circle

12.5 Ann Arbor, MI Photo Log

12.5.1 Multi-lane site – Ellsworth and State Street

Figure 12-137: East leg exit lane crossing

a) Two- lane crossing.

b) Zig-zag cut-through in island.

c) Rumble strips before crosswalk.

d) Continental crosswalk markings.

Figure 12-138: Approach to roundabout, looking west from east leg

a) Lane drop shortly past crosswalk.

b) Bike ramp merging from sidewalk into bike lane on street in foreground of photo.

Figure 12-139: Drivers' view of crosswalk

a) Stop here to pedestrians sign before crosswalk.

b) Lane ends sign shortly after crosswalk.

c) On-street bicycle lane resumes shortly after crosswalk.

Figure 12-140: View of zig-zag cut-through island

a) Detectable warning surface at opening.

b) Curbed area of island around walkway.

Figure 12-141: Rumble strips in pavement

a) Pen at bottom left for size comparison.

Figure 12-142: Entry east leg

a) Continental crosswalk marking.

b) Yield word sign pavement marking.

c) Yield sign on both sides of entry.

d) Dotted edge line at entry.

e) Chevron sign on island.

Figure 12-143: View of curb and detectable warning surface and alignment of sidewalk at east entry

a) Detectable warning surface and curb line/gutter not aligned the same.

b) DW aligned with crosswalk?

c) Short distance between crosswalk and yield sign.

Figure 12-144: Looking back at entry rumble strips and lane markings

a) Rumble strip about 20 feet before crosswalk.

b) Pavement markings with lane designation before rumble strips.

Figure 12-145: View of north crosswalk exit lanes

a) Landscape strip between sidewalk and roadway.

b) Stop here to pedestrians sign just before the crosswalk.

c) Light pole right before crosswalk.

d) Continental markings for crosswalk.

Figure 12-146: View of rumble strips and distance before crosswalk

Figure 12-147: View of another zig-zag cut-through island

Figure 12-148: North crosswalk, crossing exclusive right turn

a) Narrow island without zig zag and then wider island with zig-zag between opposing entry and exit lanes.

b) Ramp, detectable warnings and gutter/curb line not aligned with crosswalk direction here.

Figure 12-149: Exit lanes – west crosswalk (studied)

a) Rumble strips in pavement.

b) Stop here to pedestrians sign.

c) Continental crosswalk markings.

d) Lane ends sign just past crosswalk.

e) Bike lane resumes just past crosswalk.

f) Zig-zag cut-through splitter island.

Figure 12-150: Another view of exit lane crosswalk and splitter island

Figure 12-151: Pedestrian view of west crosswalk exit lane crossing

a) Curb ramp with returned curbs aligned with crosswalk direction.

b) Detectable warnings at base of ramp.

c) Crosswalk perpendicular to curb line/gutter.

Figure 12-152: Bike ramp and sidewalk view

Figure 12-153: Entry lane crosswalk from island west leg

a) Detectable warning at edge of island.

b) Gutter and curbs angle slightly right of DWalignment.

Figure 12-154: Pedestrian view of entry leg crossing west crosswalk

a) Wide crosswalk.

b) Landscaping on each side of walkway/ramp.

c) Detectable warning the full width of the ramp.

d) Curb and gutter aligned perpendicular to crosswalk.

12.5.2 Single-lane roundabout: Nixon Road and Huron Parkway

Figure 12-155: View of overhead crosswalk signs

Signs were internally illuminated at night.

Figure 12-156: View of ramp to crosswalk at exit lane with bike ramp in background

Figure 12-157: View of crosswalk studied, sidewalk and landscaping

a) Landscaping between sidewalk and road.

b) Rumble strips at exit from roundabout.

c) Crosswalk marked with transverse lines.

d) Worn brick stamped texture and color on crosswalk (see later photo).

e) Yield here to pedestrians sign before crosswalk.

f) Curb ramp with returned curbs, aligned slightly left of crosswalk.

g) Narrow splitter island.

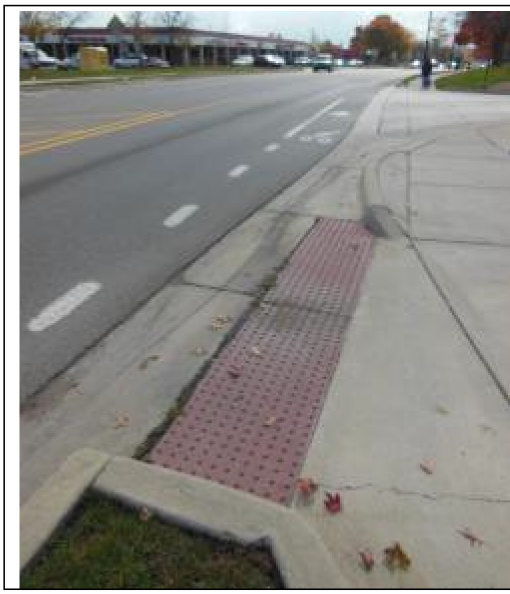

Figure 12-158: Closer view of bike ramp

a) Note how close to sidewalk it is, angle of ramp, and detectable warning surface.

b) Landscaping between street and sidewalk begins after bike ramp.

Figure 12-159: Small diameter circle

a) Truck apron in center and at entry.

b) Chevron signs on island.

c) Directional street name signs on splitters.

Figure 12-160: Drivers view of exit crosswalk – south leg

Figure 12-161: Yield signs

a) Yield sign posts with reflective tape.

b) Yield sign on left angled for driver looking left.

c) Sharkstooth yield line used at roundabout entry.

Figure 12-162: West crosswalk

Figure 12-163: View of crosswalk lighting (west crosswalk)

a) Note light over crosswalk in addition to overhead signs.

b) Overhead signs were illuminated at night.

Figure 12-164: Pedestrian view of crosswalk approach west leg

a) Landscape strip between sidewalk and street.

b) Yield here to pedestrians sign before crosswalk.

c) Overhead crosswalk signs.

d) Rumble strips in roadway.

e) Narrow splitter island.

f) Crosswalk outlined with white lines, brick color/texture in crosswalk.

Figure 12-165: Narrow splitter island

a) Cut-through.

b) Brick patterns on raised sections (same brick pattern in crosswalk).

c) Less than one foot separation in detectable warning surfaces.

d) Detectable warnings aligned with crosswalk direction.

e) Curb line and gutter slightly angled in relation to crosswalk direction.

Figure 12-166: Truck apron at entry

a) Slightly raised but very close to crosswalk.

b) Worn brick stamped pattern in crosswalk.

Figure 12-167: North crosswalk

Figure 12-168: View of east crosswalk

a) Odd alignment of island edges, not aligned with crosswalk.

b) Brick pattern in crosswalk.

c) Narrow splitter island.

Figure 12-169: East crosswalk splitter island

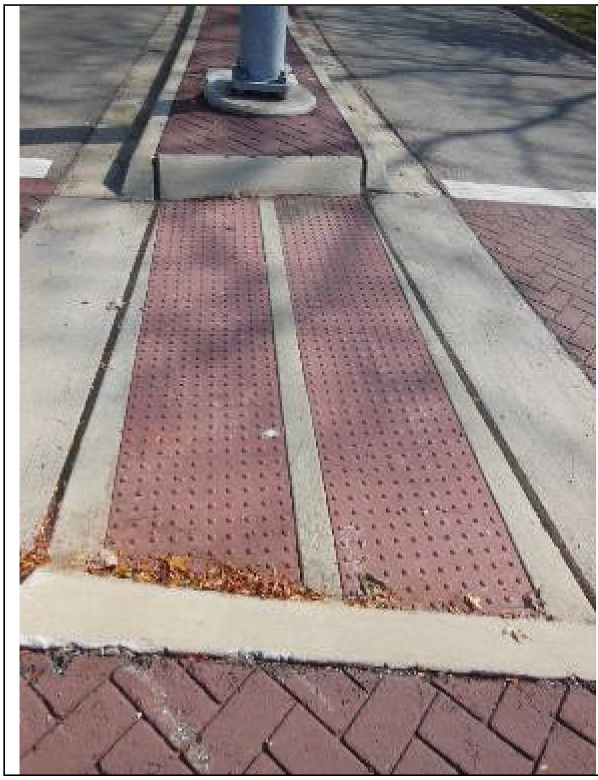

Figure 12-170: East crosswalk splitter island

a) Very narrow.

b) Inadequate separation between detectable warning surfaces.

Figure 12-171: Bike ramp on entry

a) Wrong way sign for bicyclists.

b) Short ramp.

c) Landscape strip continues past bike ramp.

12.6 Greenbelt, MD Photo Log

12.6.1 Cherrywood Lane and Metro Access Road

Figure 12-172: Driver's view on approach on west leg (Cherrywood)

a) Roundabout sign and yield ahead sign.

b) No directional signage on approach (what street).

c) Bike lane (see next photo and description)

d) Pedestrian crossing ahead sign.

e) Pedestrian crossing sign at crossing with 'hump' placard under it.

f) Wide striped median area, then raised landscaped area.

g) Directional sign for Metro station.

Figure 12-173: Bike sign and ramp to sidewalk

a) Bicycle sign.

b) No bike lane ends sign, although there's no dotted line to signify bicyclists can take lane.

c) Widened sidewalk and bike ramp to sidewalk with construction identical to curb ramp construction.

d) If bicyclists want to go left toward Metro station, they have to take a lane unless they cross at pedestrian crossing, but then sidewalk is very narrow on north side of roundabout.

e) Observed some erratic and dangerous bicyclist movements (riding on left, wrong way in circle, etc.).

Figure 12-174: Markings and signs at entry

a) Faded sharks tooth yield line.
b) Yield sign.
c) TO TRAFFIC IN CIRCLE placard below yield sign
d) Chevron sign and one-way sign on central island

Figure 12-175: Pedestrian view on approach

a) Wide sidewalk.

b) Landscaping between sidewalk and curb.

c) No indication of crosswalk location on sidewalk (blind pedestrians have to be looking for it).

d) Path narrows sign (for bicyclists?).

Figure 12-176: Narrow entry to curb ramp and crosswalk

a) Narrow, four-feet entry to ramp/crosswalk area, missed by some blind participants.

b) Wide flares on ramp (flares unnecessary with landscaping on both sides).

c) Would be better to have entry as wide as crosswalk with returned curbs on each side.

d) Detectable warnings at base of ramp.

Figure 12-177: View of pedestrian crosswalk – west crosswalk across Cherrywood looking north

a) Six-foot wide crosswalk.

b) Perpendicular curb ramp with detectable warnings.

c) Crosswalk raised as speed hump for vehicles, although slope is not really detectable underfoot to pedestrian.

d) No pedestrian refuge area between entry and exit lanes, although there are raised planted medians between each lane.

e) Ladder markings for crosswalk.

f) Speed hump markings very faded.

Figure 12-178: Uneven pavement near beginning of west crosswalk, from south

Figure 12-179: View of west leg, (leaving roundabout), looking west from crosswalk on north side of Cherrywood Lane

a) Lane ends symbol sign (W4-2)

b) BIKE LANE AHEAD sign

c) Dotted bike lane markings between lanes

d) 30 mph speed limit sign after roundabout on all legs, no sign reducing speed at roundabout.

Figure 12-180: Parallel curb ramp on north side (exit lanes)of west crosswalk

a) Parallel curb ramp in narrow sidewalk.

b) Cars felt very close to pedestrians on narrow sidewalk, particularly buses (and there were a lot of buses here).

c) Lots of cross slope on sidewalk coming around curve toward ramp.

d) Detectable warnings on curb ramp landing.

Figure 12-181: Approach from north

a) Two lanes, right lane with pavement markings RIGHT ONLY

b) Guide sign is beyond roundabout center island [To south 95-495 and left arrow] somewhat hidden by bushes; no other guide signs found.

c) Pedestrian crossing ahead warning sign.

Figure 12-182: Crosswalk not far from yield line/sign for vehicles entering roundabout from north

Figure 12-183: Median between lanes

a) Concrete island installed between right only lane and through/right lane (similar treatment present on east approach).

b) Yield signs on median island and splitter islands.

c) Placard TO TRAFFIC IN CIRCLE under yield sign.

d) Orange delineators in front of median nose.

e) Crosswalk close to yield point.

f) Pedestrian crossing sign, with HUMP placard installed beneath it (partially visible on right edge of photo).

Figure 12-184: Another view of median and crosswalk (north crossing)

a) Raised crosswalk.

b) Speed hump markings and construction visible.

c) Yield sign for left lane.

Figure 12-185: View of crosswalk north crossing

a) Ladder crosswalk markings.

b) Combo curb ramp.

c) Raised crosswalk.

d) Crosswalk not aligned perpendicular to gutter.

e) No pedestrian refuge even though there's a splitter island and there could be adequate room for a refuge.

Figure 12-186 View of exit lane crosswalk on west leg from north leg (from median between right only lane and right/through lane)

a) Note that from this point driver in right lane cannot see pedestrian standing in the ramp at the crosswalk.

b) Yield sign – not sure who driver is yielding to at that point - pedestrians?

c) Narrow sidewalk at back of curb.

Figure 12-187: East approach

a) Right only lane and right/through lane.

b) No pedestrian crosswalk on this leg.

c) Bike lane has dotted markings, then solid again ending in median nose? Should be striped out somehow?

d) Roundabout sign, yield ahead placard.

Figure 12-188: View from crosswalk of vehicles approaching from east let to north leg

a) Vehicle moving pretty quickly downhill.

b) Closest lane vehicle not visible around curve until about 50 feet before crosswalk

c) Speed hump and pedestrian sign with HUMP placard not visible more than 50 before crosswalk.

Figure 12-189: Narrowed sidewalk along south side of roundabout

12.6.2 Channelized Turn Lane Kenilworth Road and East West Highway, Greenbelt MD

Figure 12-190: Approach to intersection

a) RIGHT LANE MUST TURN RIGHT sign.

b) Pedestrian crossing warning sign.

c) Lots of truck traffic on Kenilworth Road.

Figure 12-191: Unusual placard under pedestrian warning sign: ACROSS RAMP

Figure 12-192: View of crosswalk location

a) Channelized right turn with decel lane, sloping downhill toward East West Highway.

b) Yield signs at merge point with EW Highway.

c) Pedestrian warning signs.

d) Marked crosswalk.

e) Signal controller box may block driver's view of pedestrians (from slightly further back).

Figure 12-193: Pedestrian's view on approach

a) Sidewalk at back of curb.

b) Grass on side away from street.

Figure 12-194: Pedestrian's view of approaching traffic from crosswalk

a) Note that controller blocks view of cars approaching in the right turn lane.

Figure 12-195: View of crosswalk and island

a) Parallel ramp (entire sidewalk slopes down to level with the street).

b) Detectable warning at point where sidewalk is level with the street.

c) Crosswalk with diagonal striping.

d) Narrow cut-through areas on island aligned with crosswalk direction, but much narrower than crosswalk.

e) Grass on island areas that are not cut-through.

f) APS with pushbutton locator tones on island for crossings of Kenilworth and East-West Highway.

Figure 12-196: Detectable warning on island at entry to cut-through area covered in dirt and debris

Figure 12-197: Crossing East West Highway from island

a) Narrow cut-through bordered by grass.

b) Curbs on cut-through basically aligned with direction of travel on the crosswalk.

c) Detectable warning at edge of street.

d) APS more than 10 feet from edge of street.

Figure 12-198: Crossing Kenilworth Road from island

a) Narrow cut-through area bordered by grass.

b) Lots of debris in cut-through area.

c) APS about 5 feet back from road.

d) Cut-through, gutter and detectable warning aligned with direction of travel on the crosswalk.

12.7 Cary, NC Photo Log

12.8 CTL – SW corner of Tryon Road and Kildaire Farm Road

Figure 12-199: Driver's view on approach on Tryon Road

a) RIGHT LANE MUST TURN RIGHT sign.

b) Right turn arrow lane marking.

c) Signal ahead warning sign (behind RT sign in this photo).

d) Uphill approach.

Figure 12-200: Signal ahead sign

a) Signal ahead sign with road name.

b) Other guide signs on approach.

Figure 12-201: Driver's view of CTL and pedestrian crossing

a) Right turn arrow and ONLY pavement marking.

b) Informational signs (bike route and wildlife viewing area signs).

c) No pedestrian crossing sign.

d) Marked pedestrian crosswalk (pavement markings).

Figure 12-202: Marked crosswalk is not very visible on approach

Although the crosswalk is marked with continental stripes, it is not very visible to approaching drivers. No warning sign to add more visibility.

Figure 12-203: Pedestrian approach

a) Sidewalk separated from roadway by wide landscape strip.

b) Sidewalk curves away from road, around corner, then a spur angles back to crosswalk.

c) Crosswalk is at location were pole and with signal controller is visible in this photo.

Figure 12-204: Crosswalk approach sidewalk

a) Perpendicular ramp.

b) Sidewalk all slopes toward crosswalk.

c) Grass landscape strip between sidewalk and curb on approach to crosswalk.

Figure 12-205: Crosswalk across right turn lane and view of large island area

a) Large flares on ramp wider than crosswalk area.

b) Detectable warning at base of ramp.

c) Continental markings for crosswalk.

d) Large completely paved island.

e) Signal pole in middle of island where some blind participants looked for a pushbutton (could hear the pole).

f) Standard (non-audible) pushbuttons on pedestrian signal pole near crosswalks across Kildaire Farm and Tryon.

Figure 12-206: Curb ramps and crosswalks for Tryon (front) and Kildaire Farm (to right)

a) Ramp slope and detectable warning aligned with crosswalk direction, gutter not aligned perpendicular to crosswalk.

b) Pushbuttons back more than 10 feet from both crosswalks, two buttons on same pole.

c) Darker pavement on ramp as well as detectable warnings.

d) Lots of debris and sand on detectable warning at Kildaire Farm crossing. In addition, entire corner is basically flat, not just where detectable warning is installed.

Figure 12-207: Closer view of curb ramps

a) Ramp to Kildaire Farm Rd. crossing on left, Tryon Road crossing on right.
b) Designs look like they were an attempt to align the ramps with the crosswalk, but road/ramp connection does not meet ADA requirements.

12.8.1 Roundabout – Old Apex Road and West Chatham Street, Cary, NC

Figure 12-208: Driver's view of roundabout on approach from west on Old Apex Road

a) Roundabout sign and advisory speed sign.

b) Yield ahead sign.

c) Center two way turn lane.

d) Driveway into gas station on right just before crosswalk and roundabout entry.

e) Pedestrian warning signs at crosswalk.

Figure 12-209: Pedestrian approach to west crosswalk, entry leg

a) Brick sidewalk.

b) Grass landscape strip between sidewalk and curb.

c) Ramp slope outside of sidewalk area.

Figure 12-210: West crosswalk, from south end

a) One lane entry.

b) Landscaping on both sides of ramp.

c) Brick sidewalks near roundabout.

d) Perpendicular curb ramp.

e) Detectable warning at base of ramp.

f) Ramps slope, detectable warning and gutter lined up in crosswalk direction (generally within).

g) Narrow splitter island with wide cut-through area.

h) Detectable warning surface does not cover full width of cut-through opening in island.

Figure 12-211: View of west exit crosswalk from beyond east crosswalk

Figure 12-212: Pedestrian approach to west crosswalk, exit lane

a) Grass landscape strip between sidewalk and curb.

b) Brick sidewalk, concrete curb ramp.

c) Pedestrian warning sign with downward arrow before crosswalk.

Figure 12-213: West crosswalk, looking south, exit lane crossing

a) Perpendicular ramp.

b) Brick sidewalk.

c) Sidewalk does not continue past crosswalk.

d) Ramp, DW and gutter aligned to left of crosswalk.

e) Narrow island with wide cut-through.

Figure 12-214: Illustration of pedestrian stepping past detectable warning surface that doesn't extend the full width of the cut-through in island

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13 APPENDIX F: DETAILED FIELD STUDY RESULTS

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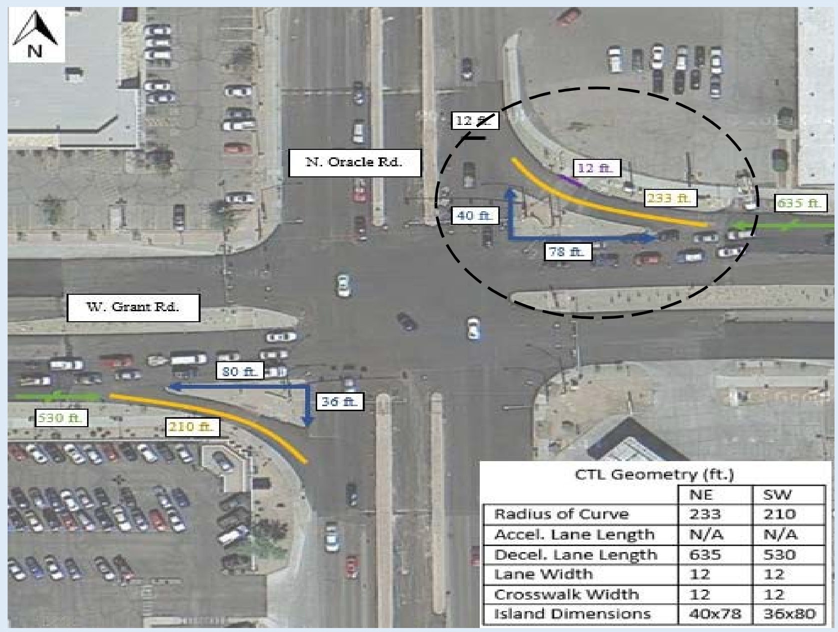
Guidelines for the Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities

NCHRP 3-78b

SITE SUMMARIES – NCHRP 03-78B – APPENDIX F

CTL - Tucson, Arizona – Grant and Oracle Road (NE approach)

Studied April 2014



Factor	Rating
Description	
Noise	OK
Low volume in turn lane, few trucks, no other sound sources	
Visibility	Concerning
Issue because of cabinets, and because crosswalk is too close to downstream end	
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volumes

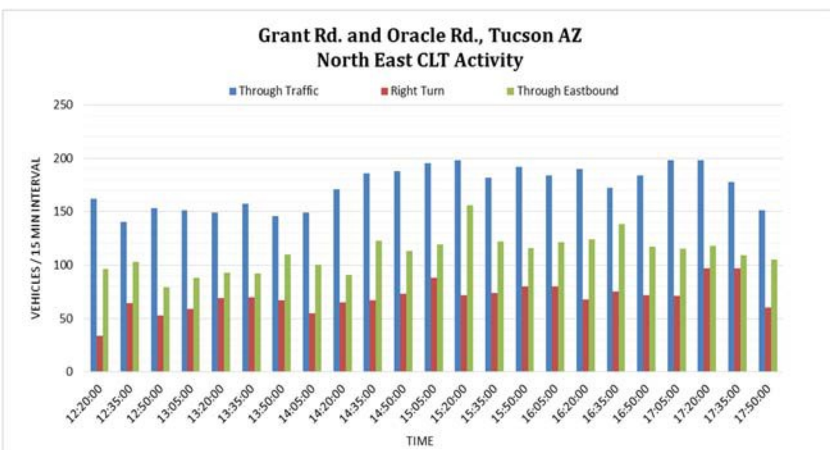


Exhibit 2: Special Feature

Site Background

This site was studied as part of trip evaluating four different channelized turn lanes in Tucson, AZ. The two studied CTLs both featured deceleration lanes, and no acceleration lanes. Both further had a raised crosswalk installed, although the design was such that vehicles could still comfortably traverse it. The southwest crosswalk featured a yield sign (for vehicles) past the crosswalk, while the yield sign at the northeast crosswalk was located at the crosswalk.

CTL - Tucson, Arizona – Grant and Oracle Road (NE approach)

Studied April 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Tucson, AZ	NE	n=36	0	0%	2	5.56%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Tucson, AZ	NE	n=36	3.00	0.56	2.56	3.80	3.43

Exhibit 5: Free-Flow Speed Statistics

Quadrant	Location	Approach Signal: Green				Approach Signal: Red			
		Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
NE	Upstream (n=30G, 30R)	31 (2.9)	23	36	34	30 (3.3)	25	36	34
	At X-walk (n=30G, 30R)	21 (2.7)	15	26	23	19 (2.4)	13	24	21

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NE	67.92%	22.22%	71.79%	67.86%

Exhibit 7: Yielding Rate

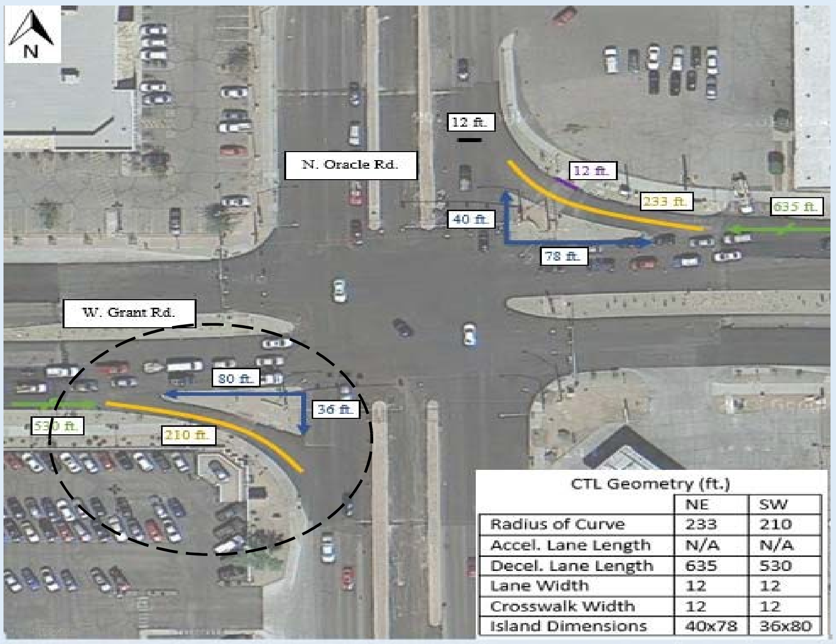
Quadrant	Blind/Sighted	Yield Rate
NE	Blind(n=29)	63%
	Sighted(n=30)	50%

Key Observations

- The NE quadrant showed higher yielding rates, despite slightly higher speeds.
- The NE quadrant further showed significantly reduced risk, despite a sight obstruction on the approach through two signal cabinets.

CTL - Tucson, Arizona – Grant and Oracle Road (SW approach)

Studied April 2014



Factor	Rating
Description	
Noise	OK
However, yield utilization suggests an issue	
Visibility	OK
Better than NE approach; two-stage movement	
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volumes

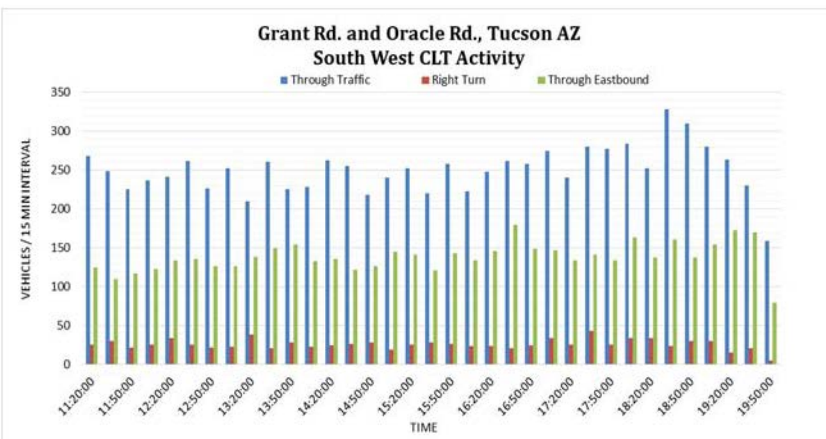


Exhibit 2: Special Feature

Raised Crosswalk SW Quadrant

Site Background

This site was studied as part of trip evaluating four different channelized turn lanes in Tucson, AZ. The two studied CTLs both featured deceleration lanes, and no acceleration lanes. Both further had a raised crosswalk installed, although the design was such that vehicles could still comfortably traverse it. The southwest crosswalk featured a yield sign (for vehicles) past the crosswalk, while the yield sign at the northeast crosswalk was located at the crosswalk.

CTL - Tucson, Arizona – Grant and Oracle Road (SW approach)

Studied April 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Tucson, AZ	SW	n=45	1	2.17%	4	8.7%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Tucson, AZ	SW	n=46	3.63	0.27	3.24	3.83	3.82

Exhibit 5: Free-Flow Speed Statistics

Quadrant	Location	Approach Signal: Green				Approach Signal: Red			
		Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
SW	Upstream (n=30G, 27R)	32 (3.4)	26	38	36	29 (3.4)	23	34	33
	At X-walk (n=39G, 30R)	20 (2.0)	15	24	22	17 (2.4)	14	24	20

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
SW	49.50%	14.00%	56.34%	65.00%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
SW	Blind(n=20)	87%
	Sighted(n=20)	70%

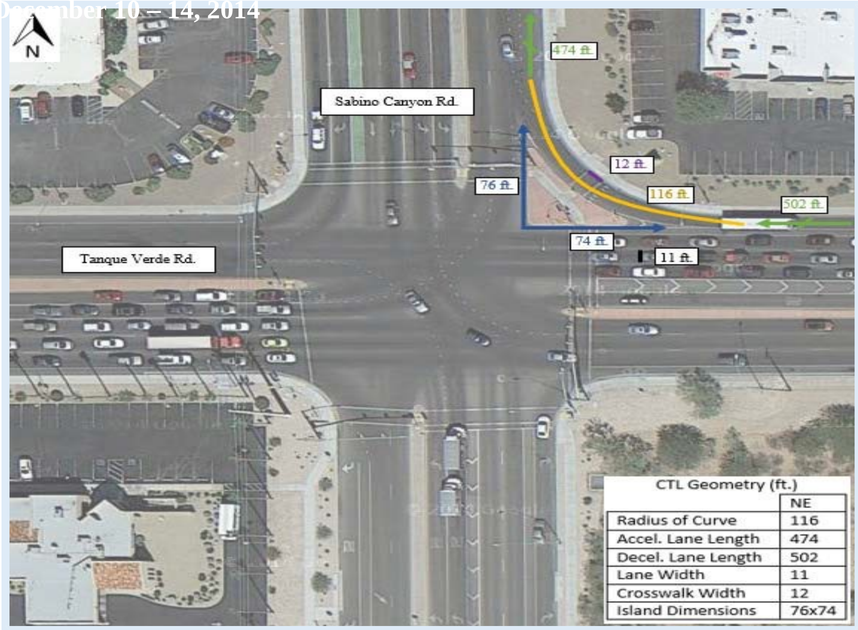
Key Observations

- The SW quadrant did not have landscaping separation posing some wayfinding challenges.
- Both islands had good wayfinding features through channelization and landscaping.

CTL - Tucson, Arizona – Sabino Canyon Road and Tanque Verde Road

Studied April 2014

December 10 – 14, 2014



Factor	Rating
Description	
Noise	OK
Easier to hear than Oracle & Grant, bigger island seemed helpful despite high traffic	
Visibility	OK
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volume

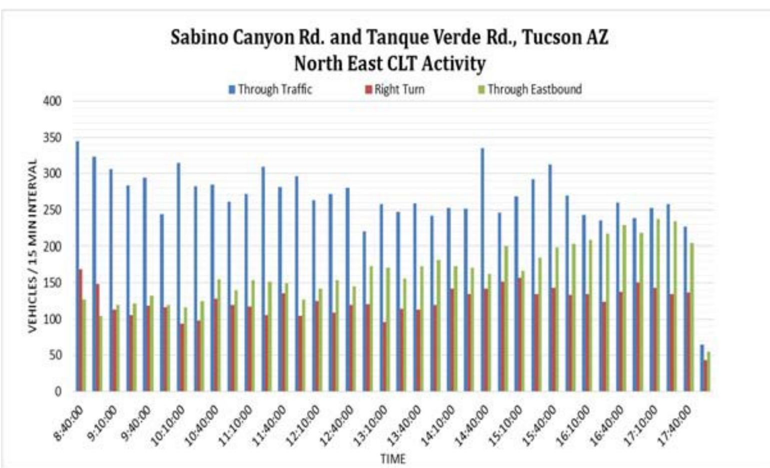
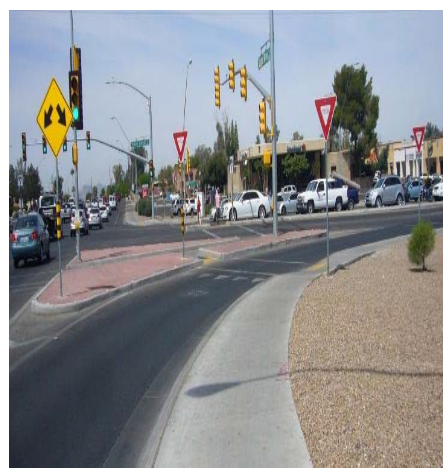


Exhibit 2: Special Feature



Site Background

This site was studied as part of trip evaluating four different channelized turn lanes in Tucson, AZ. The studied CTLs featured a deceleration lane and an acceleration lanes. A yield sign was located at the crosswalk.

CTL - Tucson, Arizona – Sabino Canyon Road and Tanque Verde

Studied April 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Tucson, AZ	NE	n=37	0	0%	3	8.11%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Tucson, AZ	NE	37	4.19	0.54	3.65	4.79	4.66

Exhibit 5: Free-Flow Speed Statistics

Location	Approach Signal: Green				Approach Signal: Red			
	Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
Upstream (n=35G, 43R)	30 (3.0)	24	35	33	28 (3.3)	21	33	32
At X-walk (n=30G, 39R)	22 (2.5)	15	26	24	19 (2.3)	13	23	20.3

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NE	46.62%	14.52%	20.45%	44.44%

Exhibit 7: Yielding Rate

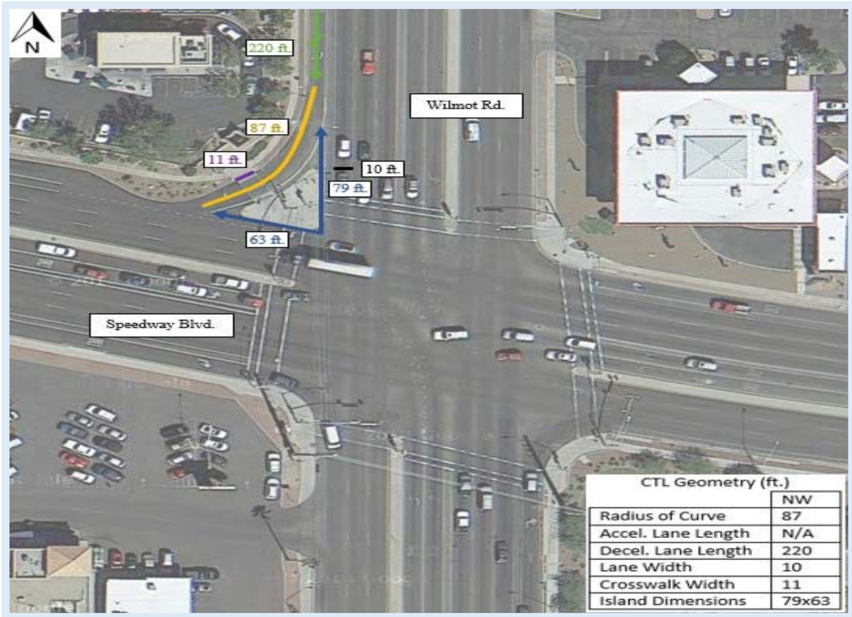
Quadrant	Blind/Sighted	Yield Rate
NE	Blind (n=30)	57%
	Sighted (n=30)	53%

Key Observations

- The site showed generally high speeds and low yielding compared to other CTLs studied in Tucson, which may be related to the large radius of curvature.
- No landscape separation is provided on the curb side, posing some wayfinding challenges.

CTL - Tucson, Arizona – Wilmot Road and Speedway Boulevard

Studied April 2014



Factor	Rating
Description	
Noise	OK
Visibility	OK
Lane Utilization	n/a

Exhibit 1: Traffic Volume

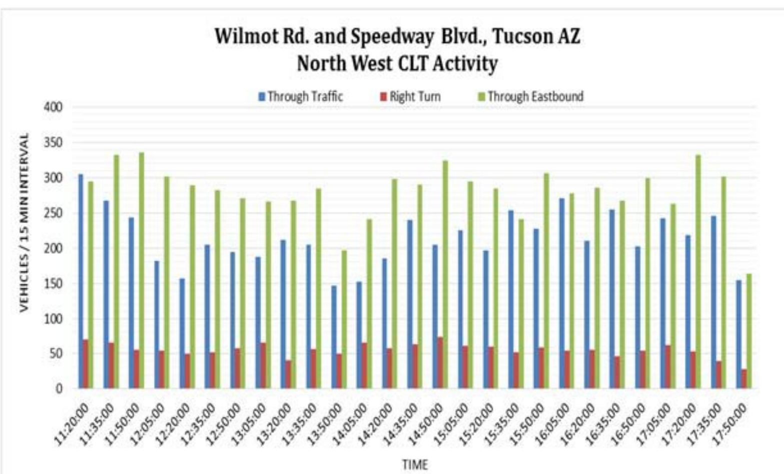


Exhibit 2: Special Feature

Site Background

This site was studied as part of trip evaluating four different channelized turn lanes in Tucson, AZ. The studied CTLs featured a deceleration lane but no acceleration lanes. A stop sign was located at the crosswalk as a vehicular safety treatment, since drivers had limited sight distance to the left when trying to merge onto Speedway Boulevard Eastbound from the CTL.

CTL - Tucson, Arizona – Wilmot Road and Speedway Boulevard

Studied April 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Tucson, AZ	NW	n=46	1	2.17%	1	2.17%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Tucson, AZ	NW	n=46	6.31	2.96	3.57	9.27	8.90

Exhibit 5: Free-Flow Speed Statistics

Location	Approach Signal: Green				Approach Signal: Red			
	Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
Upstream (n= 41G, 30R)	33 (3.71)	25	40	36	28 (3.35)	23	36	31.65
At X-walk (n= G, R)	n/a (stopped)	---	---	---	---	---	---	---

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NW	88.57%	22.58%	58.82%	75.00%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
NW	Blind(n=21)	n/a (~100%)
	Sighted(n=20)	n/a (~100%)

Key Observations

- The stop sign at the crosswalk resulted in very high yield compliance and low speeds at the crosswalk.
- The site generally showed low interventions and low delay.
- Landscape separation through gravel on the approach facilitated wayfinding.
- Lack of landscaping or cut-through on the island posed wayfinding challenges for some participants.

CTL - Boulder, Colorado – 28th Street and Canyon Boulevard

Studied July 2014

Factor	Rating
Description	
Noise	OK
Doesn't seem louder than other CTLs within Boulder	
Visibility	Concerning
Crosswalk close to downstream end creating single-stage maneuver	
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volume

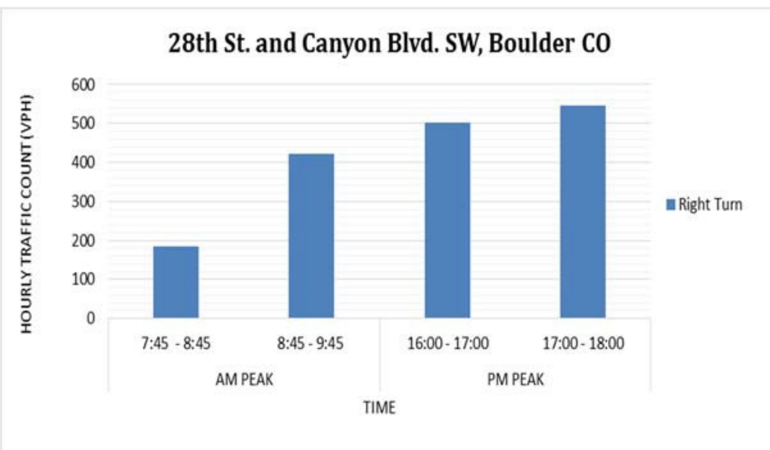


Exhibit 2: Special Feature

Site Background

This channelized turn lane (CTL) was studied as part of trip evaluating six CTLs in the Boulder, CO area. This CTL is located at the southwest quadrant of the intersection of 28th Street and Canyon Boulevard. It contains a deceleration lane, a raised crosswalk, but does not have an acceleration lane. This site was one of three of the six Boulder CTL locations that were within the city limits in the downtown area.

CTL - Boulder, Colorado – 28th Street and Canyon Boulevard

Studied July 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Boulder, CO	SW	n=48	4	8.33%	4	8.33%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Boulder, CO	SW	n=48	23.87	21.19	6.63	58.12	41.22

Exhibit 5: Free-Flow Speed Statistics

	Approach Signal: Green				Approach Signal: Red			
Location	**Avg. (St. Dev)**	**Min**	**Max**	**85%**	**Avg. (St. Dev)**	**Min**	**Max**	**85%**
Upstream (n=30G, 30R)	29(3.5)	23	35	32.5	27(3.9)	18	35	30.7
At X-walk (n=30G, 30R)	15(0.9)	14	17	16	14(1.5)	11	16	15.7

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
SW	40.34%	36.62%	19.69%	72.00%

Exhibit 7: Yielding Rate

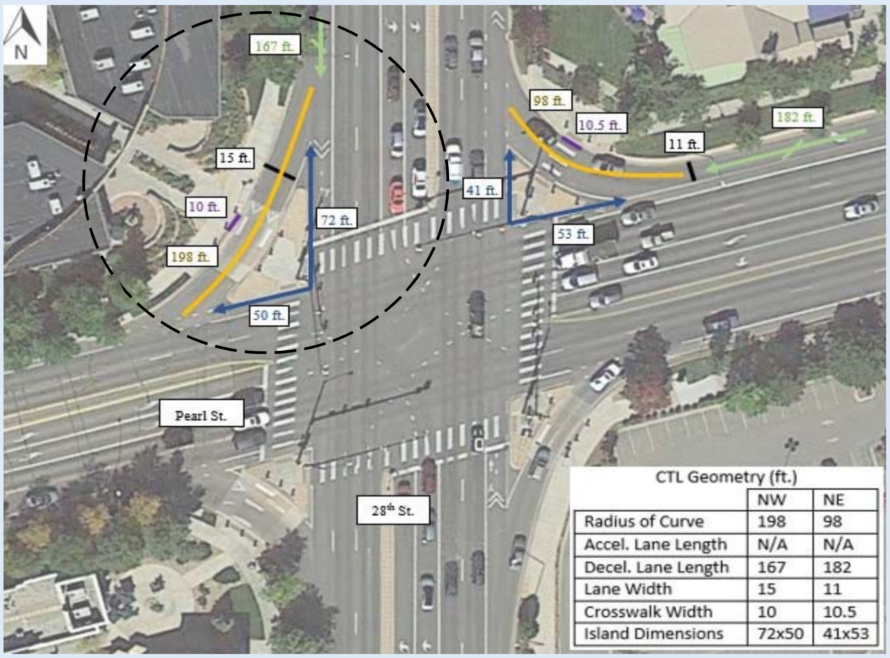
Quadrant	Blind/Sighted	Yield Rate
SW	Blind (n=25)	100%
	Sighted (n=25)	100%

Key Observations

- The raised crosswalk at this site may have helped reduce vehicle speeds, but the yielding rate remained relatively low at 40%.
- The site showed an unusually high rate of interventions, which may be related to sight distance and audibility challenges at this site.
- No separation through landscaping was provided between the sidewalk and the curb.

CTL - Boulder, Colorado – 28th Street and Pearl Street (NW approach)

Studied July 2014



	NW	NE
Radius of Curve	198	98
Accel. Lane Length	N/A	N/A
Decel. Lane Length	167	182
Lane Width	15	11
Crosswalk Width	10	10.5
Island Dimensions	72x50	41x53

Factor	Rating
Description	
Noise	OK
Visibility	OK
Sufficient storage downstream	
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volumes

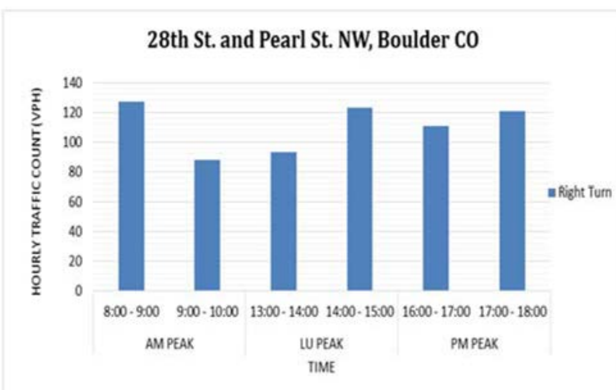


Exhibit 2: Special Feature

Site Background

The first CTL at this intersection is at the northeast quadrant of the intersection of 28th Street and Pearl Street. It contains a deceleration lane, but does not have an acceleration lane. The second CLT is at the northwest quadrant of the intersection of 28th Street and Pearl Street. It contains a deceleration lane, a raised crosswalk, but does not have an acceleration lane. These two sites were two of three of the six Boulder CTL locations that were within the city limits in the downtown area.

CTL - Boulder, Colorado – 28th Street and Pearl Street (NW approach)

Studied July 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Boulder, CO	NW	n=58	1	1.72%	0	0%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Boulder, CO	NW	n=58	15.70	15.26	2.26	43.86	26.97

Exhibit 5: Free-Flow Speed Statistics

Quadrant	Location	Approach Signal: Green				Approach Signal: Red			
		Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
NW	Upstream (n=30G, 30R)	25 (2.9)	20	30	28	21 (2.0)	17	24	23
	At X-walk (n=30G, 30R)	14 (2.5)	10	19	17	13 (1.9)	10	18	15

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NW	57.78%	38.46%	83.61%	84.31%

Exhibit 7: Yielding Rate

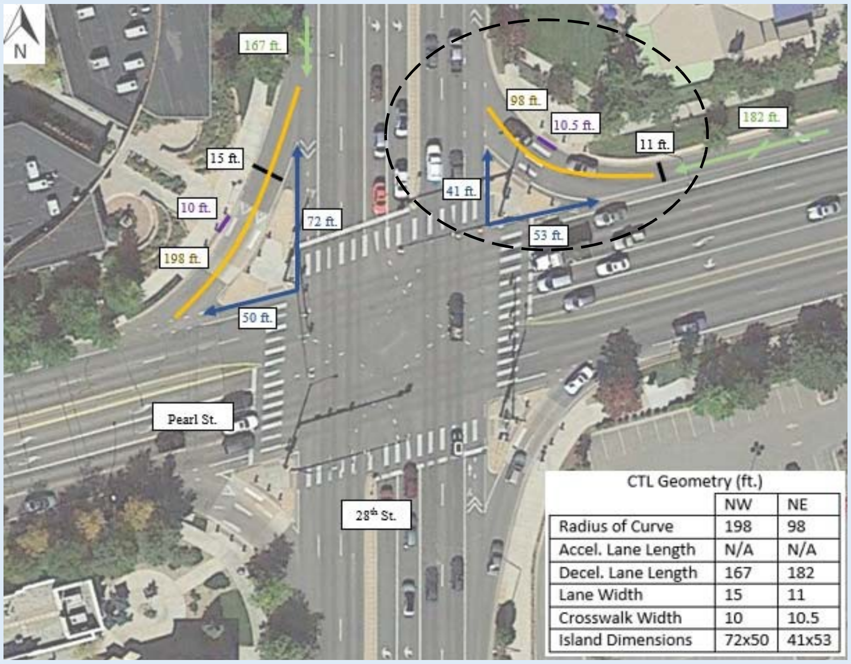
Quadrant	Blind/Sighted	Yield Rate
NW	Blind (n=45)	93%
	Sighted (n=45)	93%

Key Observations

- The NW quadrant with the raised crosswalk installed performed notably better in terms of interventions than the NE quadrant with comparable geometry, but no added treatment.
- The speeds at the crosswalk were not notable different at the two approaches, and the yielding rates were similar, and yet the NW quadrant showed safety benefits.

CTL - Boulder, Colorado – 28th Street and Pearl Street (NE approach)

Studied July 2014



	NW	NE
Radius of Curve	198	98
Accel. Lane Length	N/A	N/A
Decel. Lane Length	167	182
Lane Width	15	11
Crosswalk Width	10	10.5
Island Dimensions	72x50	41x53

Factor	Rating
Description	
Noise	OK
Low turning traffic	
Visibility	Concerning
Single-stage, angle very different, driver sight distance for conflict vehicle is different	
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volumes

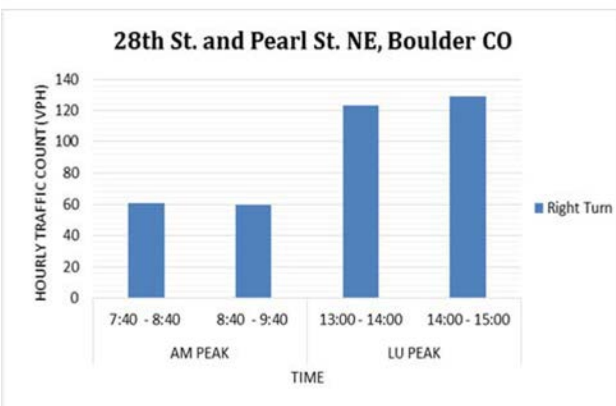


Exhibit 2: Special Feature

Site Background

The first CTL at this intersection is at the northeast quadrant of the intersection of 28th Street and Pearl Street. It contains a deceleration lane, but does not have an acceleration lane. The second CLT is at the northwest quadrant of the intersection of 28th Street and Pearl Street. It contains a deceleration lane, a raised crosswalk, but does not have an acceleration lane. These two sites were two of three of the six Boulder CTL locations that were within the city limits in the downtown area.

CTL - Boulder, Colorado – 28th Street and Pearl Street (NE approach)

Studied July 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Boulder, CO	NE	n=59	5	8.47%	7	11.86%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Boulder, CO	NE	n=59	12.15	7.68	3.01	22.66	18.45

Exhibit 5: Free-Flow Speed Statistics

Quadrant	Location	Approach Signal: Green				Approach Signal: Red			
		Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
NE	Upstream (n=30G, 30R)	26 (2.2)	22	30	27	20 (2.7)	16	25	24
	At X-walk (n=30G, 30R)	15 (1.9)	12	18	17	13 (2.4)	10	18	16

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NE	65.96%	51.61%	78.00%	87.18%

Exhibit 7: Yielding Rate

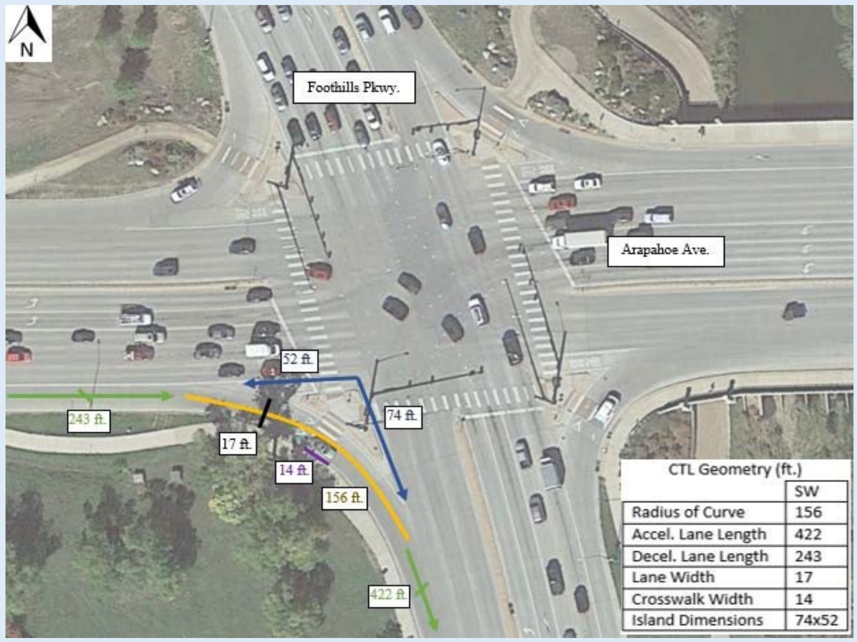
Quadrant	Blind/Sighted	Yield Rate
NW	Blind (n=45)	93%
	Sighted (n=45)	93%

Key Observations

- The NW quadrant with the raised crosswalk installed performed notably better in terms of interventions than the NE quadrant with comparable geometry, but no added treatment.
- The speeds at the crosswalk were not notable different at the two approaches, and the yielding rates were similar, and yet the NW quadrant showed safety benefits.

CTL - Boulder, Colorado – Foothills Parkway and Arapahoe Avenue

Studied July 2014



Factor	Rating
Description	
Noise	OK
Easy to hear	
Visibility	OK
Good	
Lane Utilization	n/a
n/a because approach is single lane	

Site Background

This channelized turn lane (CTL) was studied as part of trip evaluating six CTLs in the Boulder, CO area. It is at the southwest quadrant of the intersection of Foothills Parkway and Arapahoe Avenue. It contains a deceleration lane, a raised crosswalk, but does not have an acceleration lane. This site was one of three of the six Boulder CTL locations that were outside the city limits along an urban arterial corridor.

Exhibit 1: Traffic Volume

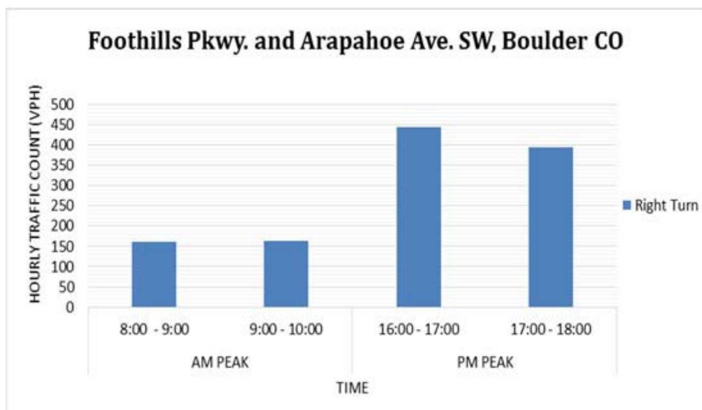


Exhibit 2: Special Feature

CTL - Boulder, Colorado – Foothills Parkway and Arapahoe

Studied July 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Boulder, CO	SW	n=60	0	0%	2	3.33%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Boulder, CO	SW	n=60	14.56	9.63	3.48	29.57	23.58

Exhibit 5: Free-Flow Speed Statistics

Location	Approach Signal: Green				Approach Signal: Red			
	Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
Upstream (n=22G, 30R)	33(3.6)	25	39	36.9	35(3.6)	28	45	38
At X-walk (n=26G, 34R)	21(4.0)	12	30	25	22(3.2)	15	30	25.1

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
SW	32.41%	45.63%	53.26%	59.18%

Exhibit 7: Yielding Rate

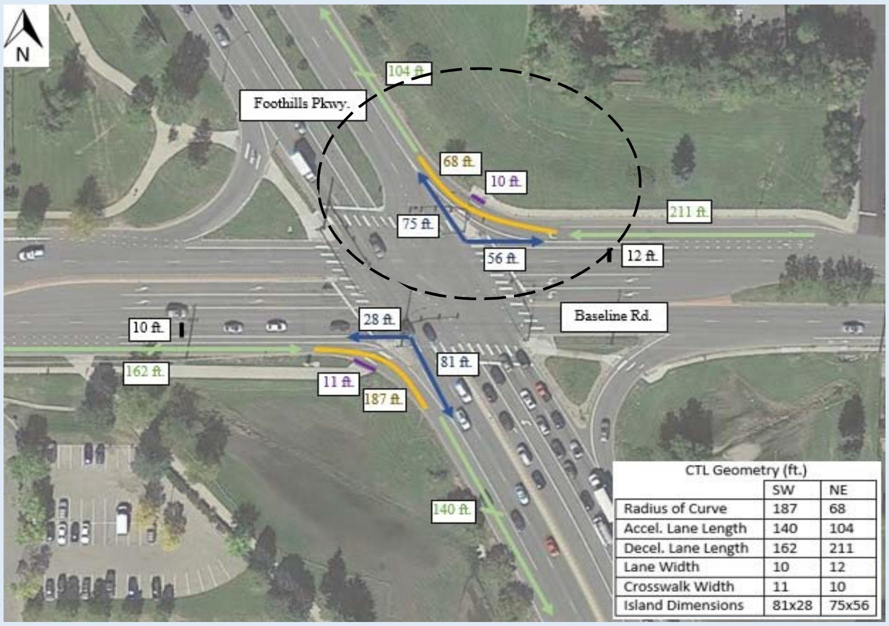
Quadrant	Blind/Sighted	Yield Rate
SW	Blind (n=20)	75%
	Sighted (n=20)	70%

Key Observations

- The raised crosswalk at the site did not result in high yielding rates to pedestrians, and still allowed speeds in excess of 20mph.
- No interventions were recorded at this location.
- There was no landscaping separation between the sidewalk and the curb at this location.

CTL - Boulder, Colorado – Foothills and Baseline Road (NE approach)

Studied July 2014



Factor	Rating
Description	
Noise	OK
Visibility	OK
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volumes

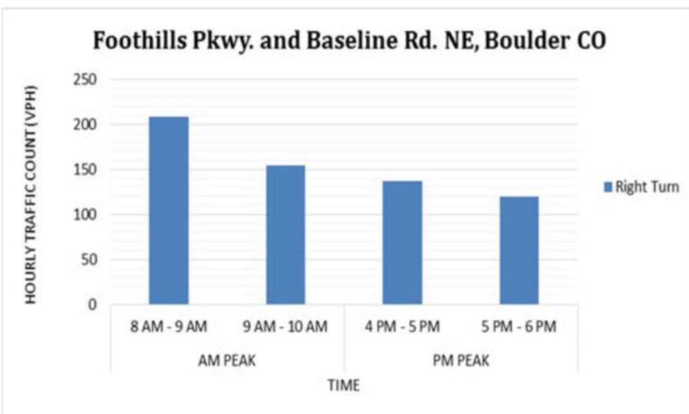


Exhibit 2: Special Feature

Site Background

This site features two channelized turn lanes (CTLs). The first CTL is at the northeast quadrant of the intersection of Foothills Parkway and Baseline Road. It contains a deceleration lane, an acceleration lane and sound strip treatment. The second CTL is at the southwest quadrant of the intersection of Foothills Parkway and Baseline Road. It contains a deceleration lane, an acceleration lane and a raised crosswalk. These sites were two of three of the six Boulder CTL locations that were outside the city limits along an urban arterial corridor.

CTL - Boulder, Colorado – Foothills and Baseline Road (NE approach)

Studied July 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Boulder, CO	NE, no TRMT	n=59	0	0%	1	1.69%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Boulder, CO	NE	n=59	12.97	13.95	4.40	39.54	23.09

Exhibit 5: Free-Flow Speed Statistics

Quadrant	Location	Approach Signal: Green				Approach Signal: Red			
		Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
NE	Upstream (n=9G, 30R)	33(6.0)	26	41	40.4	31 (3.3)	24	37	34
	At X-walk (n=16G, 28R)	25(3.4)	18	32	28.5	22(3.5)	15	30	25

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NE	36.05%	48.39%	81.54%	73.58%

Exhibit 7: Yielding Rate

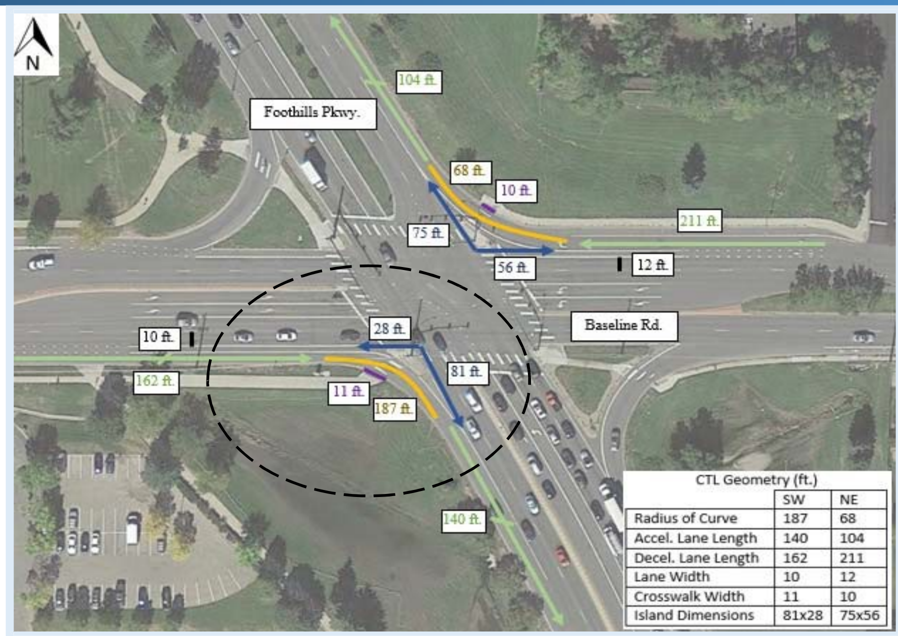
Quadrant	Blind/Sighted	Yield Rate
NE	Blind (n=21)	81%
	Sighted (n=20)	75%

Key Observations

- Some participants expressed a positive experience through the added auditory feedback from the sound strips in the SW quadrant.
- The overall performance of the CTL with sound strips was only marginally better than the one without the treatment.
- Drivers tended to try and avoid the sound strips by merging into the CTL late.
- Yielding at these locations was quite low compared to other sites in Boulder.

CTL - Boulder, Colorado – Foothills and Baseline Road (SW approach)

Studied July 2014



Factor	Rating
Description	
Noise	OK
Visibility	OK
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volumes

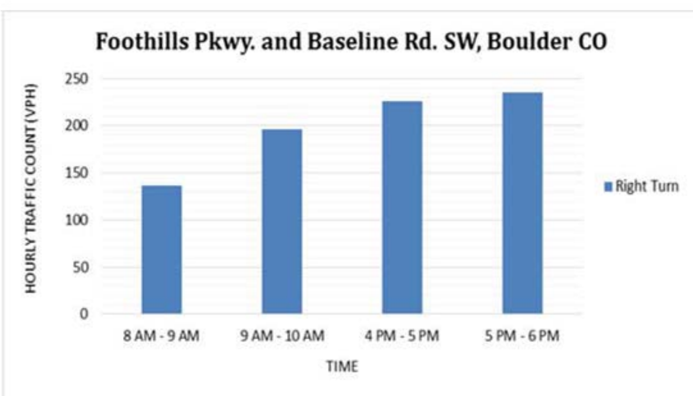


Exhibit 2: Special Feature

Site Background

This site features two channelized turn lanes (CTLs). The first CTL is at the northeast quadrant of the intersection of Foothills Parkway and Baseline Road. It contains a deceleration lane, an acceleration lane and sound strip treatment. The second CTL is at the southwest quadrant of the intersection of Foothills Parkway and Baseline Road. It contains a deceleration lane, an acceleration lane and a raised crosswalk. These sites were two of three of the six Boulder CTL locations that were outside the city limits along an urban arterial corridor.

CTL - Boulder, Colorado – Foothills and Baseline Road (SW approach)

Studied July 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Boulder, CO	SW, Sound Strip	n=60	0	0%	2	3.33%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Boulder, CO	SW	n=60	9.82	5.17	1.70	16.39	13.85

Exhibit 5: Free-Flow Speed Statistics

Quadrant	Location	Approach Signal: Green				Approach Signal: Red			
		Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
SW	Upstream (n=24G, 31R)	28(4.2)	20	41	31	29(5.8)	20	45	32.5
	At X-walk (n=23G, 30R)	20(2.6)	15	25	22.7	18(3.5)	11	26	20

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
SW	30.48%	59.38%	76.81%	75.47%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
SW	Blind (n=20)	95%
	Sighted (n=20)	85%

Key Observations

- Some participants expressed a positive experience through the added auditory feedback from the sound strips in the SW quadrant.
- The overall performance of the CTL with sound strips was only marginally better than the one without the treatment.
- Drivers tended to try and avoid the sound strips by merging into the CTL late.
- Yielding at these locations was quite low compared to other sites in Boulder.

CTL - Cary, North Carolina – Kildaire Farm Road and Tyron Road

Studied November 2014

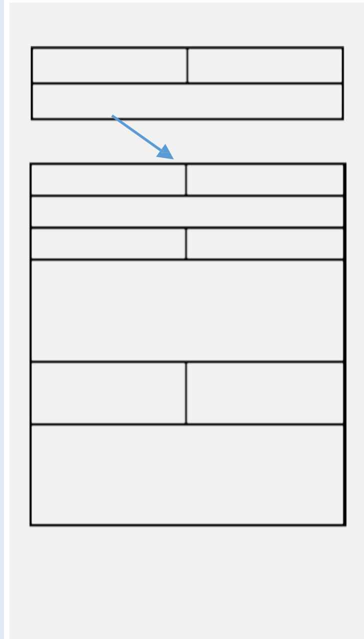
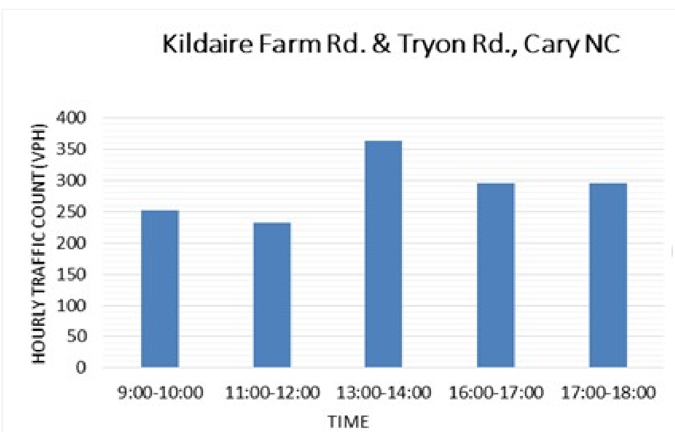


Exhibit 1: Traffic Volume

Exhibit 2: Special Feature



Site Background

This channelized turn lane is at the southwest quadrant of the intersection of Kildaire Farm Road and Tyron Road in Cary, North Carolina. It features a deceleration lane, but no acceleration lane, and no pedestrian signage at the crosswalk. Kildaire Farm Road features an uphill grade in advance of the CTL.

CTL - Cary, North Carolina – Kildaire Farm Road and Tyron Road

Studied November 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Cary, NC	SW	n=41	2	4.88%	5	12.20%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Cary, NC	SW	n=41	16.01	7.86	7.37	24.80	22.24

Exhibit 5: Free-Flow Speed Statistics

Location	Approach Signal: Green				Approach Signal: Red			
	Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
Upstream (n=23G, 30R)	38 (6.0)	21	50	42	34.8 (4.5)	26	48	39
At X-walk (n=30G, 31R)	15.2 (1.4)	12	17	17	13.5 (1.3)	10	16	15

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
SW	46.77%	31.03%	60.00%	45.83%

Exhibit 7: Yielding Rate

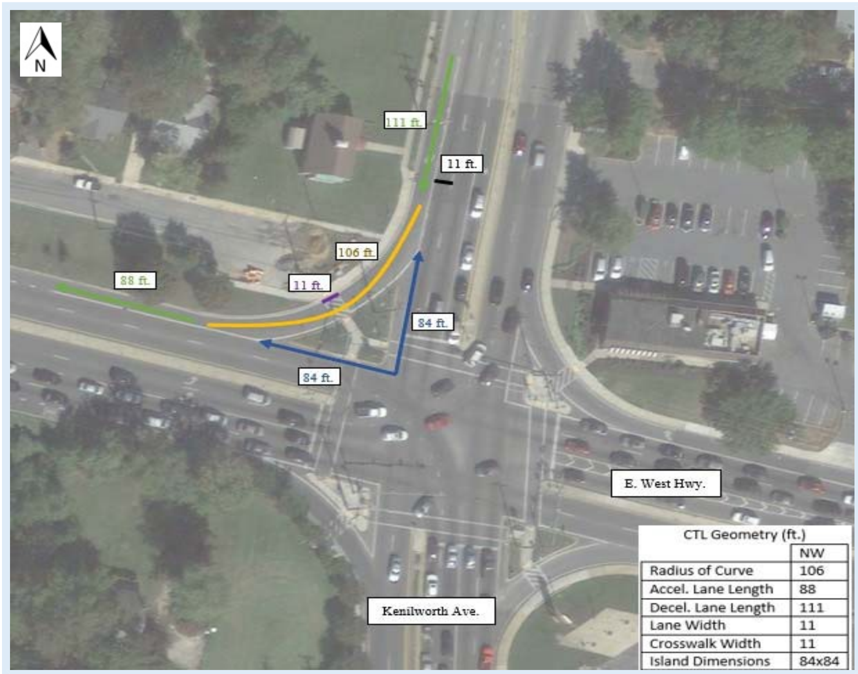
Quadrant	Blind/Sighted	Yield Rate
SW	Blind (n=24)	58%
	Sighted (n=25)	45%

Key Observations

- The upgrade along the approach toward the CTL, and the position of the crosswalk made it difficult for drivers to see pedestrians.
- The large splitter island, without landscaping or cut-through walkway, posed significant wayfinding challenges for the participants.

CTL - Greenbelt, Maryland – Kenilworth Avenue and East-West

Studied September 2014



Factor	Rating
Description	
Noise	Concerning
High noise	
Visibility	Concerning
Not ideal visibility	
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volume

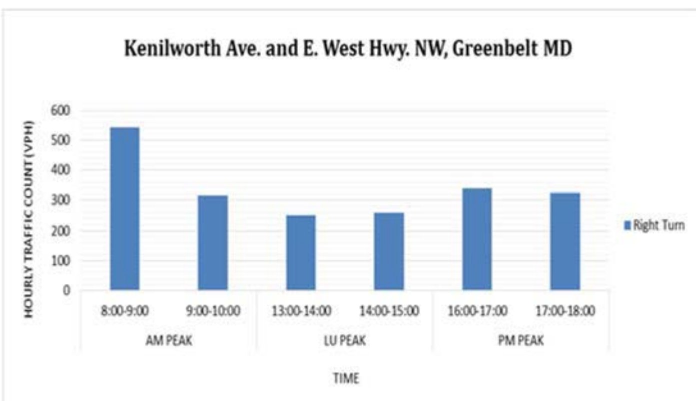


Exhibit 2: Special Feature

Site Background

This channelized turn lane (CTL) is at northwest quadrant of the intersection of Kenilworth Avenue and West Highway Street in Greenbelt, Maryland. The site features a deceleration lane and an acceleration lane. No further treatment is installed beyond standard pedestrian signage at crosswalk.

CTL - Greenbelt, Maryland – Kenilworth Avenue and East-West

Studied September 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Greenbelt MD	NW	n=48	5	10.42%	6	12.50%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Greenbelt MD	NW	n=48	20.05	18.69	3.98	52.40	37.63

Exhibit 5: Free-Flow Speed Statistics

Location	Approach Signal: Green				Approach Signal: Red			
	Avg. (St. Dev)	Min	Max	85%	Avg. (St. Dev)	Min	Max	85%
Upstream (n= 16G, 29R)	28(6.2)	14	36	34	29(4.8)	19	38	34
At X-walk (n= 16G, 29R)	17(2.8)	12	22	19.5	15(2.6)	10	21	17.6

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
NW	23.21%	43.59%	84.51%	60.00%

Exhibit 7: Yielding Rate

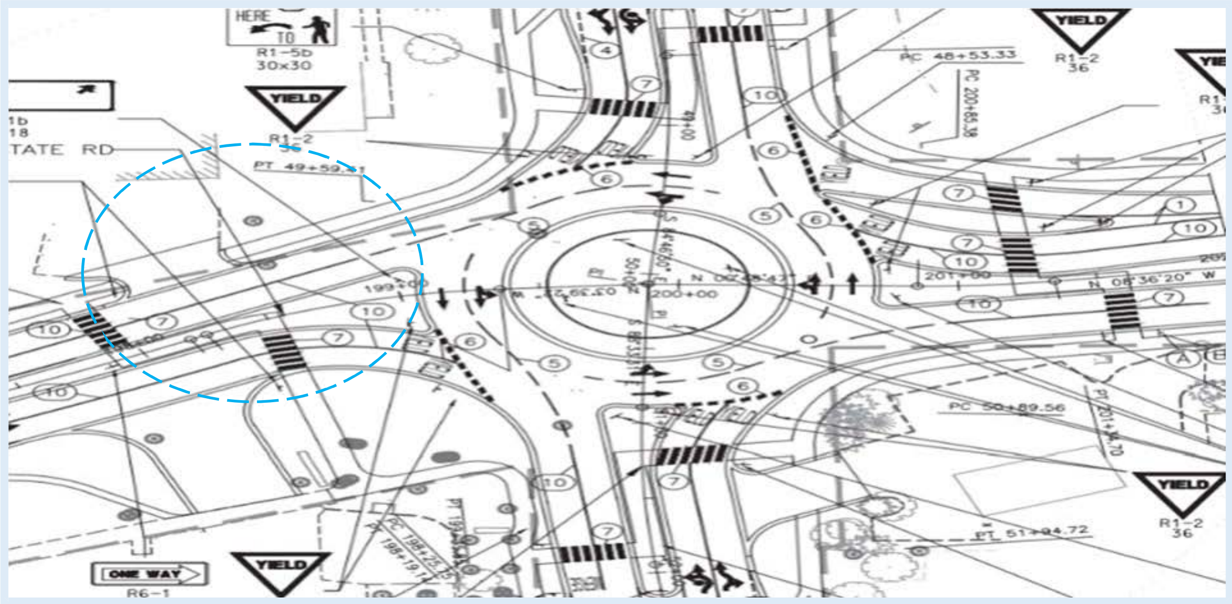
Quadrant	Blind/Sighted	Yield Rate
NW	Blind (n=30)	80%
	Sighted (n=30)	53%

Key Observations

- The intersection adjacent to the CTL featured frequent heavy vehicle activity, resulting in a loud ambient noise level and difficulty hearing vehicles in the turn lane.
- The yielding rate at the site was quite low at 23%.
- This CTL showed the highest overall intervention rate of all studied CTLs in the project at 10.4%.
- There was no separation between sidewalk and curb, posing wayfinding challenges for several participants.
- Participants also expressed difficulties orienting themselves on the large splitter island.

RBT - Ann Arbor, Michigan – Ellsworth and State Road (Entry)

Studied October 2014



Site Background

This two-lane roundabout site is at State St. and Ellsworth Road. It is a true two-lane roundabout with an offset-left design (i.e. higher deflection at entry, and relatively straight exits). The crosswalks at this location are staggered (zig-zag), with the exit leg moved approximately 40' further away from the circle. State Road has a speed limit of 35mph and a daily volume of 31,500 north of the intersection and 17,600 south of the intersection. Ellsworth Road has a speed limit of 45 mph and a daily traffic volume of 15,600 east and 13,000 west of intersection.

The roundabout is outfitted with grooved rumble strips in advance of the crosswalk at a distance of approximately 20-30’ before the crosswalk markings. Presumably, these rumble strips are intended to alert drivers of the upcoming crosswalk.

Exhibit 1: Traffic Volume

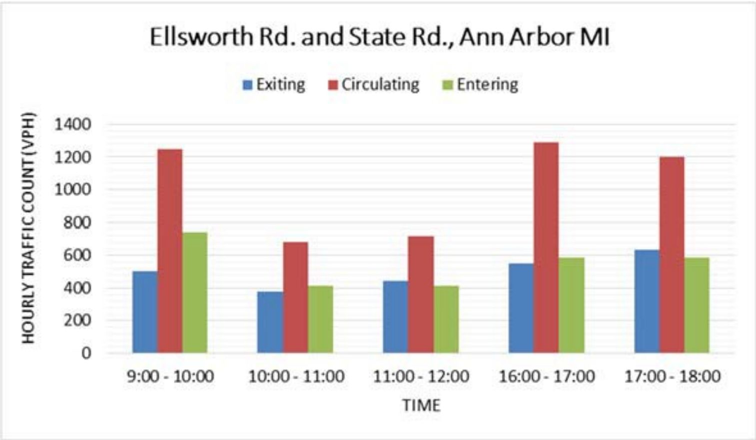


Exhibit 2: Special Feature

RBT - Ann Arbor, Michigan – Ellsworth and State Road (Entry)

Studied October 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Ann Arbor, MI	West Entry	n=32	0	0%	0	0%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Ann Arbor, MI	West Entry	n=32	7.85	4.76	3.40	14.25	11.67

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Entry (n=30)	18 (2.0)	15	24	20

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
West Entry	78.26%	52.78%	57.14%	83.33%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
Entry	Blind (n=25)	28%
	Sighted (n=25)	36%

Key Observations

- The two-lane roundabout featured slow vehicular speed and high yielding at the entry, but fast speeds and low yielding at the exit.
- The rumble strips were difficult to hear outside of the vehicle at the slow travel speeds, and further were placed very close to the crosswalk, which gave little reaction time for pedestrians.
- No interventions were recorded at the entry leg, but 3.1% at the exit leg.

RBT - Ann Arbor, Michigan – Ellsworth and State Road (Exit)

Studied October 2014

Factor	Rating
Description	
Noise	Concerning
High exiting traffic, some trucks, lots of honking	
Visibility	Concerning
Right turn challenge close to crosswalk (despite offset)	
Lane Utilization	OK

Site Background

This two-lane roundabout site is at State and Ellsworth Roads. It is a true two-lane roundabout with an offset-left design (i.e. higher deflection at entry, and relatively straight exits). The crosswalks at this location are staggered (zig-zag), with the exit leg moved approximately 40' further away from the circle. State Road has a speed limit of 35mph and a daily volume of 31,500 north of the intersection and 17,600 south of the intersection. Ellsworth Road has a speed limit of 45 mph and a daily traffic volume of 15,600 east and 13,000 west of intersection.

The roundabout is outfitted with grooved rumble strips in advance of the crosswalk at a distance of approximately 20-30' before the crosswalk markings. Presumably, these rumble strips are intended to alert drivers of the upcoming crosswalk.

Exhibit 1: Traffic Volume

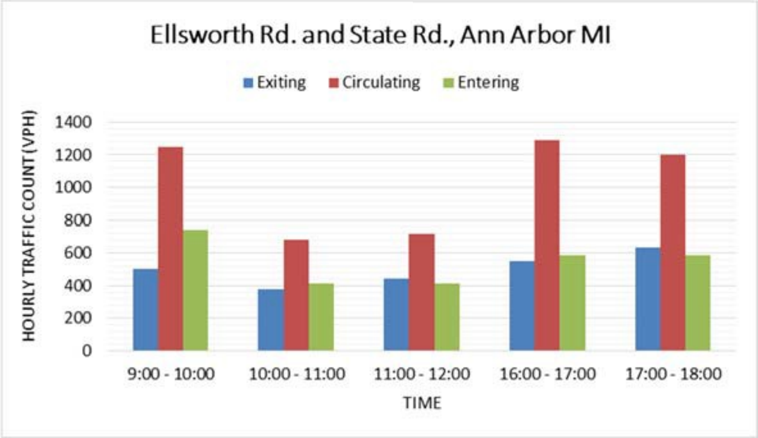


Exhibit 2: Special Feature

RBT - Ann Arbor, Michigan – Ellsworth and State Road (Exit)

Studied October 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Ann Arbor, MI	West Exit	n=32	1	3.13%	6	18.75%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Ann Arbor, MI	West Exit	n=32	9.93	2.23	7.88	12.93	11.73

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Exit (n=30)	27 (5.1)	18	36	33

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
West Exit	8.00%	68.75%	32.31%	95.24%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
Exit	Blind (n=25)	24%
	Sighted (n=25)	28%

Key Observations

- The two-lane roundabout featured slow vehicular speed and high yielding at the entry, but fast speeds and low yielding at the exit.
- The rumble strips were difficult to hear outside of the vehicle at the slow travel speeds, and further were placed very close to the crosswalk, which gave little reaction time for pedestrians.
- No interventions were recorded at the entry leg, but 3.1% at the exit leg.

RBT - Ann Arbor, Michigan – Nixon Road and Huron Parkway (Entry)

Studied October 2014

	RN	RC	RX
SB	103	103	88
NB	96	94	82

Exhibit 1: Traffic Volume

Exhibit 2: Special Feature

Site Background

This single-lane site is at Huron Parkway and Nixon Road. It has single-lane approaches on all four legs and standard crosswalks approximately 20’ from the circulatory roadway. A set of four rumble strips is milled approximately 50’ prior to each crosswalk to alert drivers and provide an auditory queue for pedestrians.

RBT - Ann Arbor, Michigan – Nixon Road and Huron Parkway (Entry)

Studied October 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Ann Arbor, MI	South Entry	n=40	0	0%	2	5%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Ann Arbor, MI	South Entry	n=40	5.78	3.11	3.04	9.35	9.11

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
Entry (n=30)	15 (2.5)	12	22	17

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
South Entry	82.35%	72.68%	76.00%	100%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
Entry	Blind (n=20)	100%
	Sighted (n=25)	96%

Key Observations

- The single-lane roundabout featured very slow vehicular speed and generally high yielding compliance from drivers.
- Frequent pedestrian activity was observed at the site, raising driver expectations of pedestrians.
- The rumble strips were difficult to hear outside of the vehicle at the slow travel speeds, and further were placed very close to the crosswalk, which gave little reaction time for pedestrians.
- No interventions were recorded at either the entry or the exit legs.

RBT - Ann Arbor, Michigan – Nixon Road and Huron Parkway (Exit)

Studied October 2014

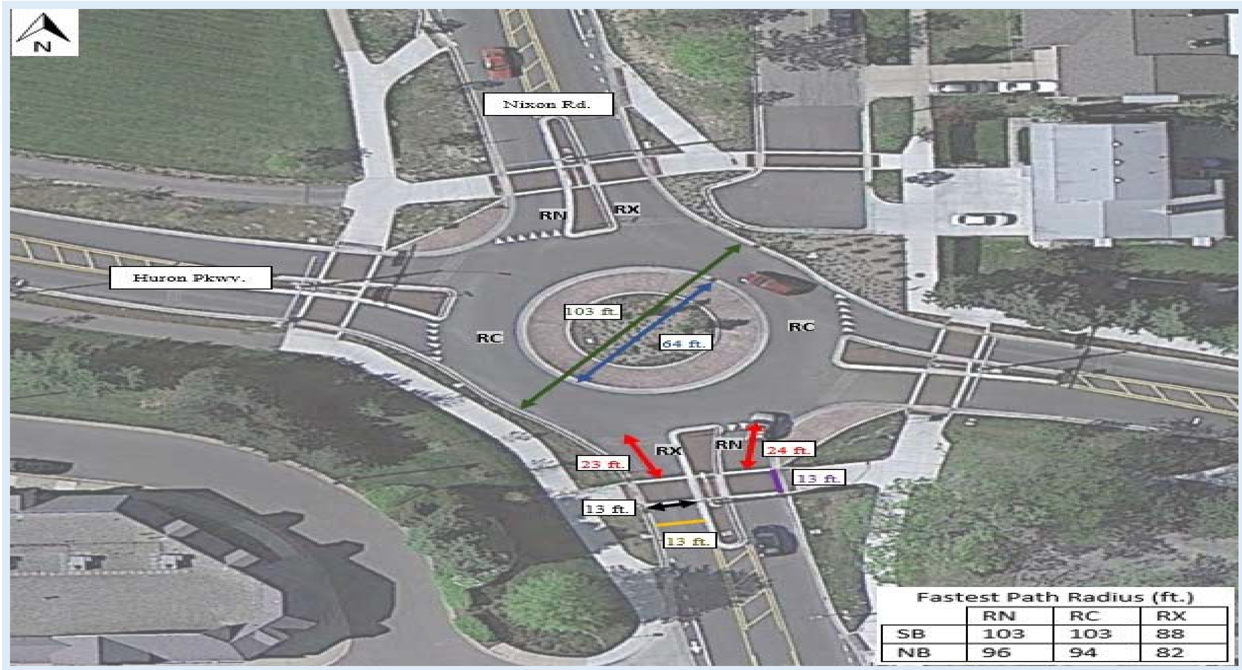
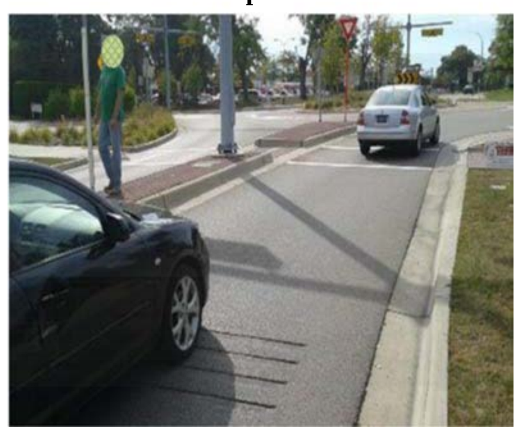


Exhibit 1: Traffic Volume

Exhibit 2: Special Feature



Site Background

This single-lane site is at Huron Parkway and Nixon Road. It has single-lane approaches on all four legs and standard crosswalks approximately 20’ from the circulatory roadway. A set of four rumble strips is milled approximately 50’ prior to each crosswalk to alert drivers and provide an auditory queue for pedestrians.

RBT - Ann Arbor, Michigan – Nixon Road and Huron Parkway (Exit)

Studied October 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Ann Arbor, MI	South Exit	n=40	0	0%	2	5%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Ann Arbor, MI	South Exit	n=40	8.39	8.79	2.66	23.08	15.31

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
Exit (n=30)	16 (2.2)	11	22	18

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
South Exit	45.45%	78.75%	72.73%	100%

Exhibit 7: Yielding Rate

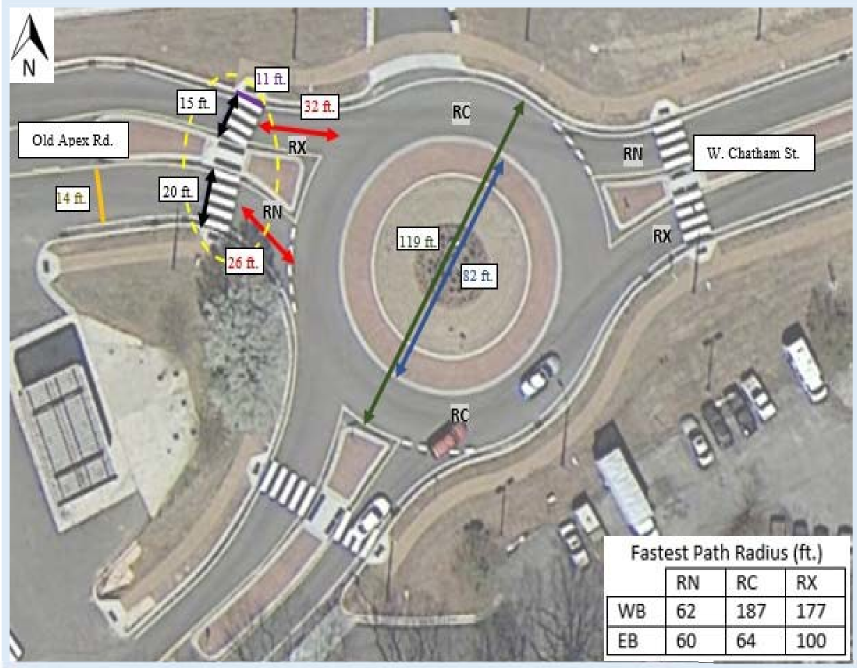
Quadrant	Blind/Sighted	Yield Rate
Exit	Blind (n=20)	95%
	Sighted (n=25)	52%

Key Observations

- The single-lane roundabout featured very slow vehicular speed and generally high yielding compliance from drivers.
- Frequent pedestrian activity was observed at the site, raising driver expectations of pedestrians.
- The rumble strips were difficult to hear outside of the vehicle at the slow travel speeds, and further were placed very close to the crosswalk, which gave little reaction time for pedestrians.
- No interventions were recorded at either the entry or the exit legs.

RBT - Cary, North Carolina – Old Apex Road and West Chatham (Entry)

Studied November 2014



Factor	Rating
Description	
Noise	OK
Visibility	OK
Lane Utilization	OK

Exhibit 1: Traffic Volume

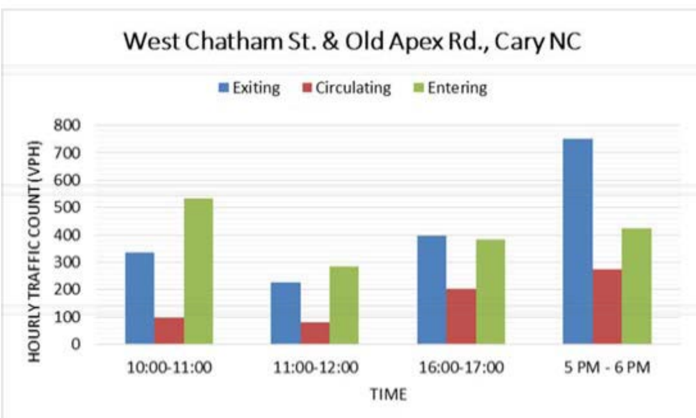


Exhibit 2: Special Feature

Site Background

This single-lane roundabout is at the intersection of Old Apex Road and West Chatham Street in Cary, North Carolina. This three-legged roundabouts has no additional treatments installed.

RBT - Cary, North Carolina – Old Apex Road and West Chatham (Entry)

Studied November 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Cary, NC	West Entry	n=40	1	2.50%	3	7.50%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Cary, NC	West Entry	n=40	11.35	4.59	5.53	15.87	15.02

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Entry (n=30)	18(0.78)	16	19	19

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
West Entry	61.36%	61.04%	58.33%	90.48%

Exhibit 7: Yielding Rate

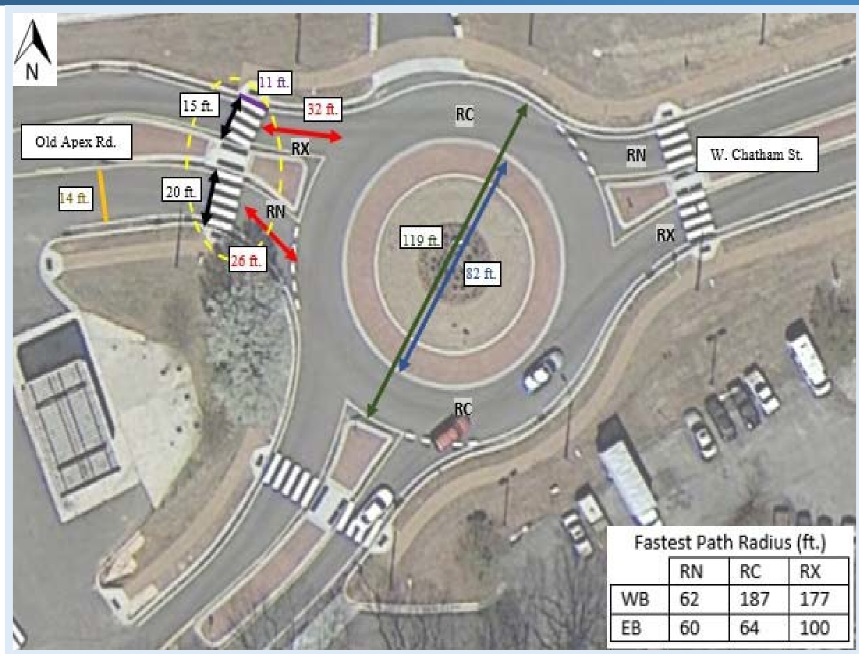
Quadrant	Blind/Sighted	Yield Rate
Entry	Blind (n=25)	56%
	Sighted (n=25)	40%

Key Observations

- Detectable warnings don’t extend all the way across the crossing, and some participants missed them because of that.
- Exiting traffic at roundabout appears to mask some of the auditory information for making decisions at the entry point to the roundabout.
- Some participants experienced long delays and waiting for quiet periods until the exit vehicles had passed.
- Deflection and curvature at the entry helps keep speeds down. Both entry and exit speeds are slow with high yielding.
- Entering traffic does not have clear visibility of the circulating lane, partially due to the vertical alignment.
- Some participants stepped up on the island and were not comfortable stepping back into splitter island, because they thought it was roadway. The island surface should be something the clearly is not a walkable surface (i.e. landscaping, gravel, etc.) but not concrete, asphalt, etc.

RBT - Cary, North Carolina – Old Apex Road and West Chatham (Exit)

Studied November 2014



Factor	Rating
Description	
Noise	OK
Visibility	Concerning
Crosswalk is close to circle	
Lane Utilization	OK

Exhibit 1: Traffic Volume

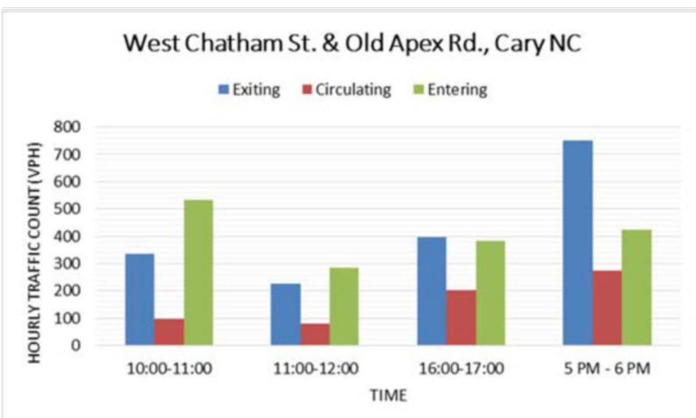


Exhibit 2: Special Feature

Site Background

This single-lane roundabout is at the intersection of Old Apex Road and West Chatham Street in Cary, North Carolina. This three-legged roundabouts has no additional treatments installed.

RBT - Cary, North Carolina – Old Apex Road and West Chatham (Exit)

Studied November 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Cary, NC	West Exit	n=41	2	4.88%	2	4.88%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Cary, NC	West Exit	n=41	11.68	2.22	10.20	15.48	13.28

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Exit (n=30)	21(1.34)	17	23	22

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
West Exit	32.20%	67.00%	43.90%	83.33%

Exhibit 7: Yielding Rate

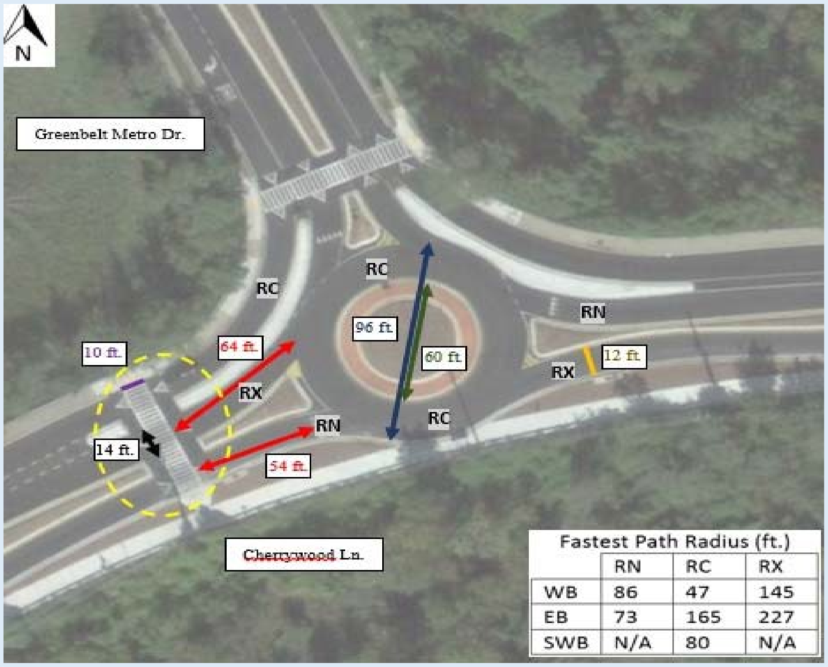
Quadrant	Blind/Sighted	Yield Rate
Exit	Blind (n=25)	52%
	Sighted (n=25)	56%

Key Observations

- Detectable warnings don't extend all the way across the crossing, and some participants missed them because of that.
- Exiting traffic at roundabout appears to mask some of the auditory information for making decisions at the entry point to the roundabout.
- Some participants experienced long delays and waiting for quiet periods until the exit vehicles had passed.
- Deflection and curvature at the entry helps keep speeds down. Both entry and exit speeds are slow with high yielding.
- Entering traffic does not have clear visibility of the circulating lane, partially due to the vertical alignment.
- Some participants stepped up on the island and were not comfortable stepping back into splitter island, because they thought it was roadway. The island surface should be something the clearly is not a walkable surface (i.e. landscaping, gravel, etc.) but not concrete, asphalt, etc.

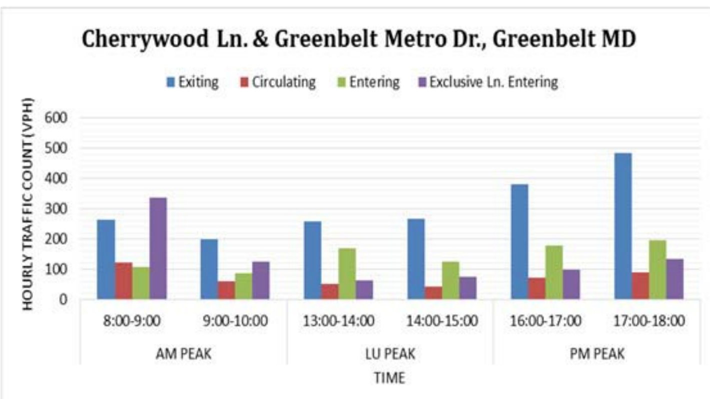
RBT - Greenbelt, Maryland – Cherrywood and Greenbelt (Entry)

Studied September 2014



Factor	Rating
Description	
Noise	Concerning
Exiting traffic made it difficult to hear entry	
Visibility	OK
Lane Utilization	n/a
n/a because approach is single lane	

Exhibit 1: Traffic Volume Exhibit 2: Special Feature



Site Background

This roundabout is at the intersection of Cherrywood Lane and Greenbelt Metro Drive in Greenbelt, Maryland. It contains slip lanes and raised crosswalks. The west approach entry and exit legs of this site were studied.

RBT - Greenbelt, Maryland – Cherrywood and Greenbelt (Entry)

Studied September 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Greenbelt, MD	West Entry	n=48	1	2.08%	1	2.08%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Greenbelt, MD	West Entry	n=48	24.02	28.51	5.45	80.54	38.77

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Entry (n=30)	17.3 (3.3)	12	26	20

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
West Entry	41.94%	38.47%	42.16%	88.37%

Exhibit 7: Yielding Rate

Quadrant	Blind/Sighted	Yield Rate
Entry	Blind (n=20)	90%
	Sighted (n=25)	92%

Key Observations

- The Raised Crosswalk resulted in slowing of vehicles at the crosswalk.
- The channelized turn lane from north to west saw frequent platoons of vehicles as drivers were leaving the Metro Station north of the roundabout.
- The site saw frequent pedestrian and bicycle activity from travelers walking/biking to and from the Metro station.
- The splitter island did not feature detectable warning surfaces, resulting in wayfinding challenges and confusion expressed by several participants.
- No landscaping was provided to separate the sidewalk from the curb at the exit leg, and only hardscaping was present on the entry.

RBT - Greenbelt, Maryland – Cherrywood and Greenbelt (Exit)

Studied September 2014

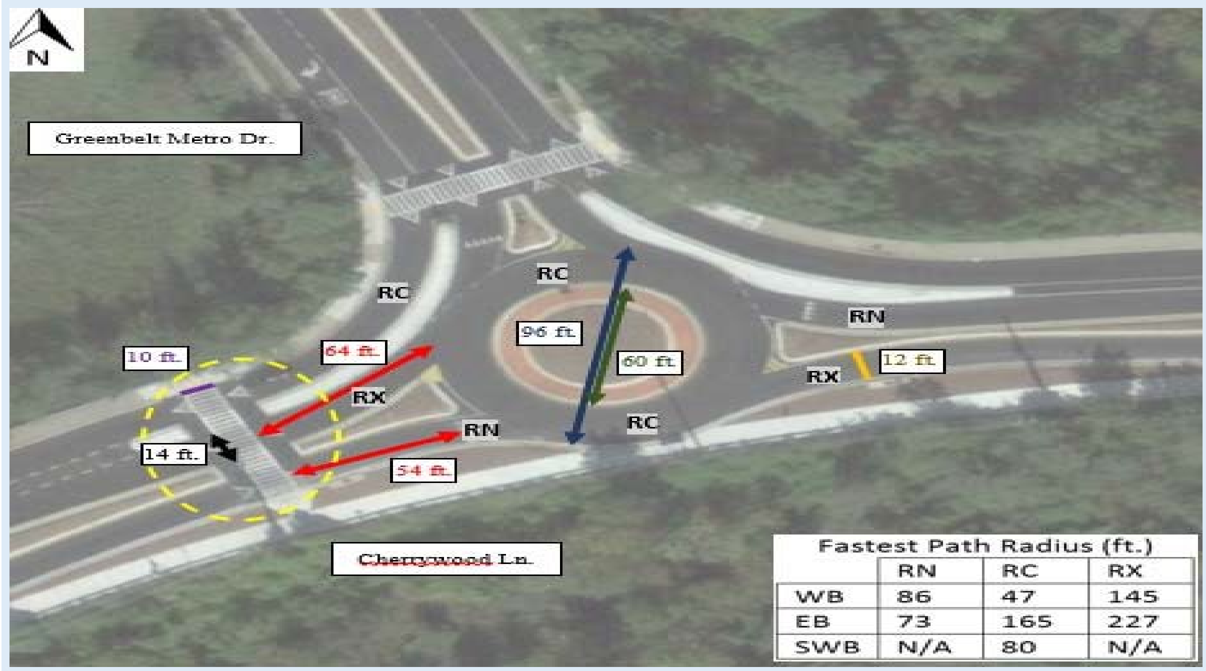
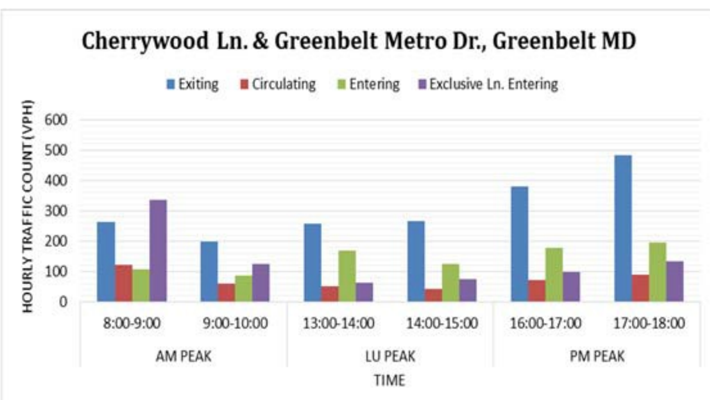


Exhibit 1: Traffic Volume Exhibit 2: Special Feature



Site Background

This roundabout is at the intersection of Cherrywood Lane and Greenbelt Metro Drive in Greenbelt, Maryland. It contains slip lanes and raised crosswalks. The west approach entry and exit legs of this site were studied.

RBT - Greenbelt, Maryland – Cherrywood and Greenbelt (Exit)

Studied September 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Greenbelt, MD	West Exit	n=50	2	4.00%	7	14%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Greenbelt, MD	West Exit	n=50	26.16	18.94	8.71	58.44	43.05

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Exit (n=30)	16.5 (3.2)	11	28	18

Exhibit 6: Yield and Gap Rates

Quadrant	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
West Exit	13.68%	30.77%	45.21%	63.64%

Exhibit 7: Yielding Rate

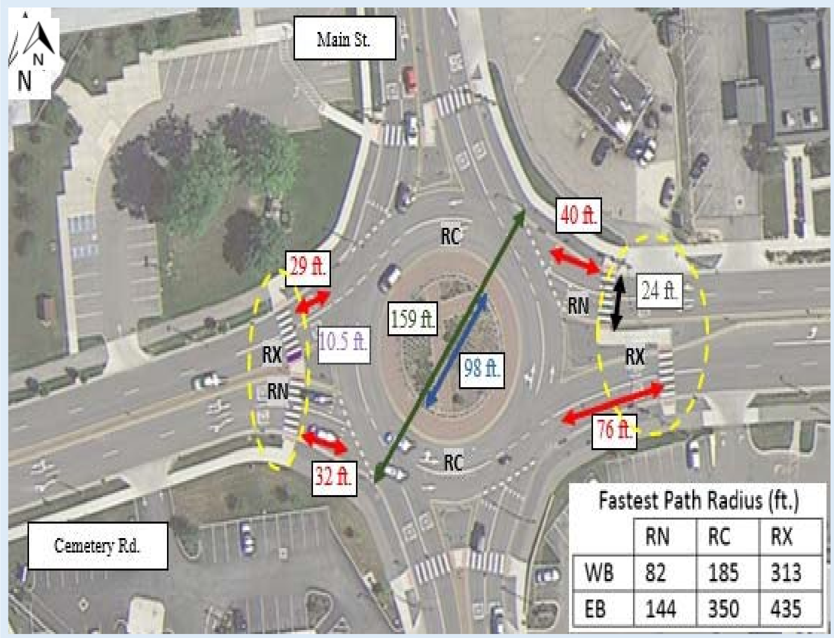
Quadrant	Blind/Sighted	Yield Rate
Exit	Blind (n=27)	56%
	Sighted (n=25)	41%

Key Observations

- The Raised Crosswalk resulted in slowing of vehicles at the crosswalk.
- The channelized turn lane from north to west saw frequent platoons of vehicles as drivers were leaving the Metro Station north of the roundabout.
- The site saw frequent pedestrian and bicycle activity from travelers walking/biking to and from the Metro station.
- The splitter island did not feature detectable warning surfaces, resulting in wayfinding challenges and confusion expressed by several participants.
- No landscaping was provided to separate the sidewalk from the curb at the exit leg, and only hardscaping was present on the entry.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (W Entry)

Studied May 2014



Factor	Rating
Description	
Noise	OK
Elevated	
Visibility	Concerning
Overlapping decision points	
Lane Utilization	Imbalanced

Exhibit 1: Traffic Volumes

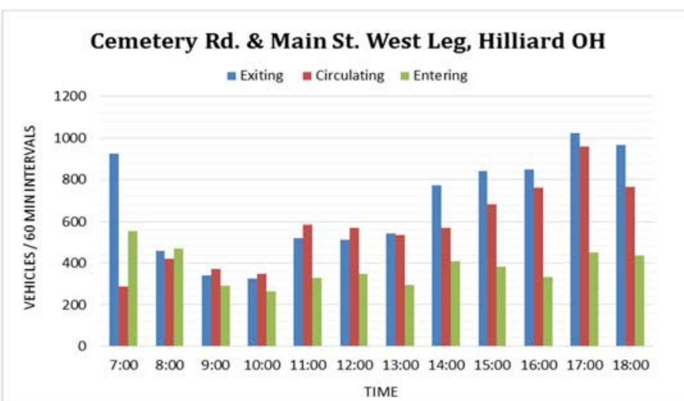


Exhibit 2: Special Feature

Site Background

This roundabout has two-lane entries and exits at all approaches and is outfitted with in-road yield-to-pedestrian warning signs. The east approach features an offset exit leg, while the west approach has more standard crosswalk geometry. The east approach further has overhead flashing beacons for a school crossing, but these devices were not active during the study.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (W Entry)

Studied May 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Hilliard, OH	West Entry	n=53	1	1.9%	13	25%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Hilliard, OH	West Entry	n=53	14.80	14.46	3.95	42.86	23.42

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Entry (n=30)	16.4 (2.2)	13.0	21.0	19.0

Exhibit 6: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Utilization Rate	Crossable Gap Utilization Rate
West Entry	63.64%	38.57%	28.00%	78.57%

Exhibit 7: Yielding Rate

Approach	Entry/Exit	Blind/Sighted	Yield Rate
West	Entry	Blind (n=25)	N/A
		Sighted (n=25)	N/A

Key Observations

- A high school was located at the north-west corner of the roundabout.
- Traffic pattern and driving behavior was different during morning, mid-day and evening, slower, more cautious traffic during morning and aggressive droving during peak hour and evening.
- West leg both entry and exit resulted in high rate of intervention and risky events.
- The roundabout was located in a vicinity of another roundabout.
- The roundabout has a history of failure to yield at entry and high crash rate (mostly PDOs).
- The roundabout get very congestion during afternoon/evening peak hour.
- Lane drops upstream and downstream of the roundabout and an inefficient signal located downstream are a few of the causes of gridlock.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (W Exit)

Studied May 2014

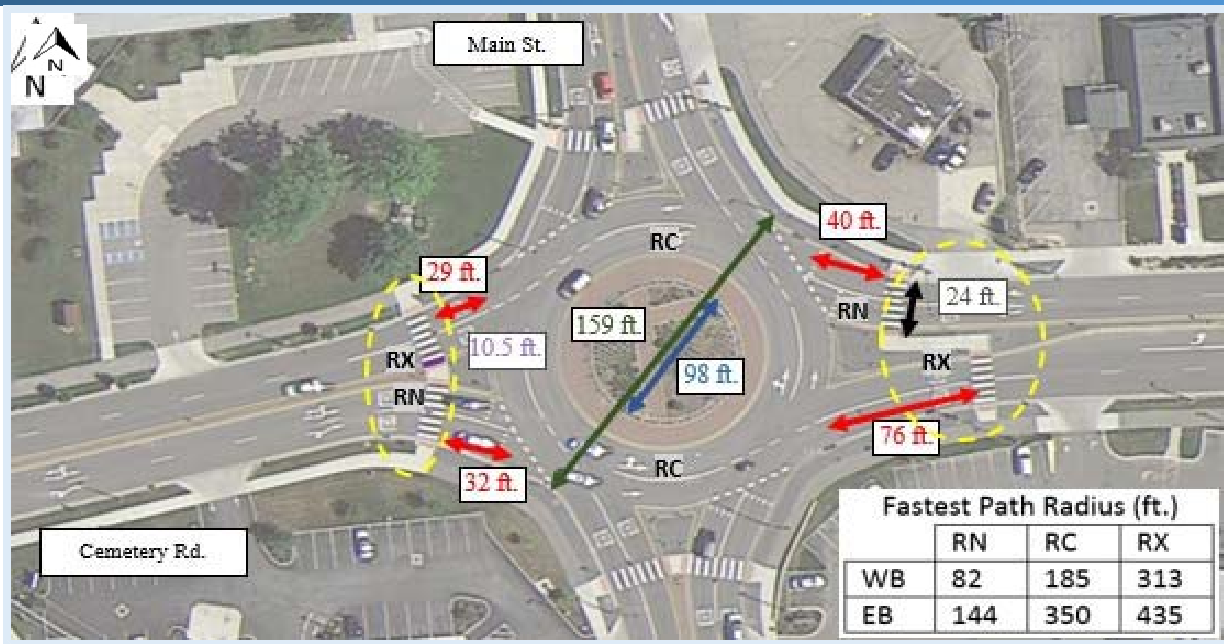


Exhibit 1: Traffic Volumes

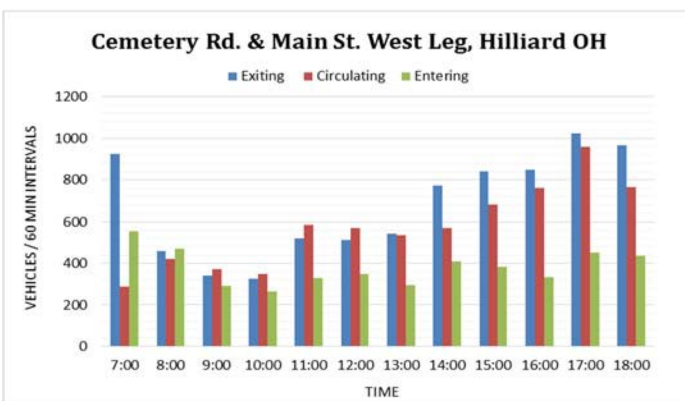


Exhibit 2: Special Feature

Site Background

This roundabout has two-lane entries and exits at all approaches and is outfitted with in-road yield-to-pedestrian warning signs. The east approach features an offset exit leg, while the west approach has more standard crosswalk geometry. The east approach further has overhead flashing beacons for a school crossing, but these devices were not active during the study.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (W Exit)

Studied May 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Hilliard, OH	West Exit	n=56	8	14%	6	11%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Hilliard, OH	West Exit	n=56	17.86	8.87	6.79	32.68	25.61

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
West Exit (n=30)	20.8 (3.2)	16.0	30.0	24.0

Exhibit 6: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Utilization Rate	Crossable Gap Utilization Rate
West Exit	21.27%	42.11%	9.62%	80.00%

Exhibit 7: Yielding Rate

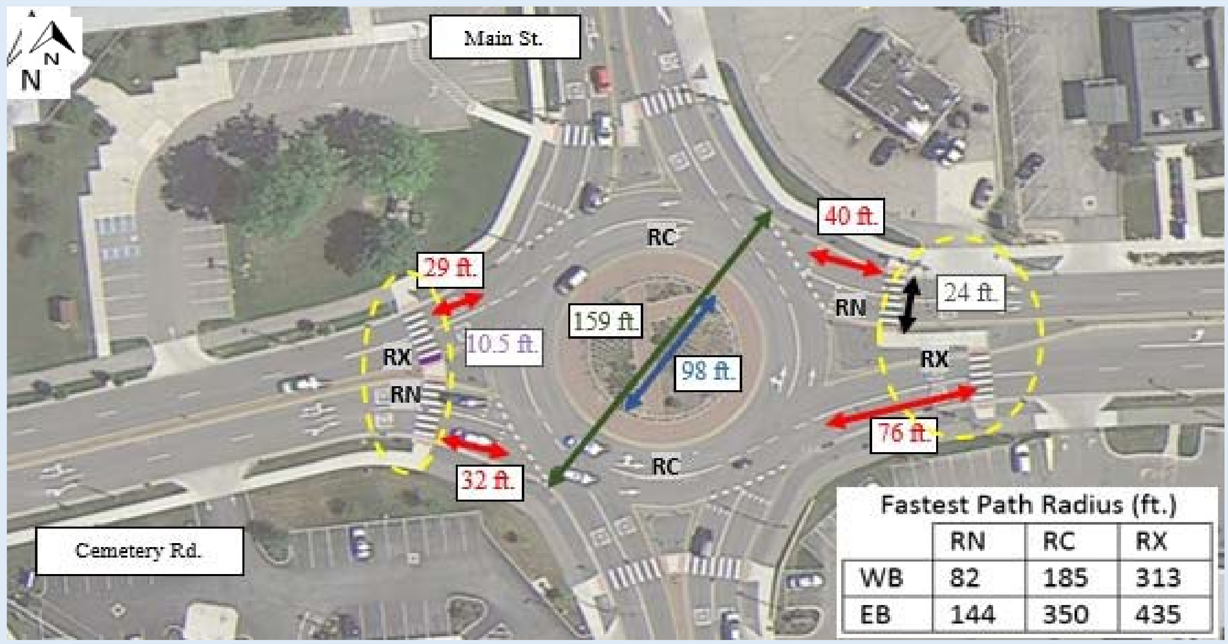
Approach	Entry/Exit	Blind/Sighted	Yield Rate
West	Exit	Blind (n=25)	45%
		Sighted (n=25)	25%

Key Observations

- A high school was located at the north-west corner of the roundabout.
- Traffic pattern and driving behavior was different during morning, mid-day and evening, slower, more cautious traffic during morning and aggressive droving during peak hour and evening.
- West leg both entry and exit resulted in high rate of intervention and risky events.
- The roundabout was located in a vicinity of another roundabout.
- The roundabout has a history of failure to yield at entry and high crash rate (mostly PDOs).
- The roundabout get very congestion during afternoon/evening peak hour.
- Lane drops upstream and downstream of the roundabout and an inefficient signal located downstream are a few of the causes of gridlock.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (E Entry)

Studied May 2014



	RN	RC	RX
WB	82	185	313
EB	144	350	435

Exhibit 1: Traffic Volumes

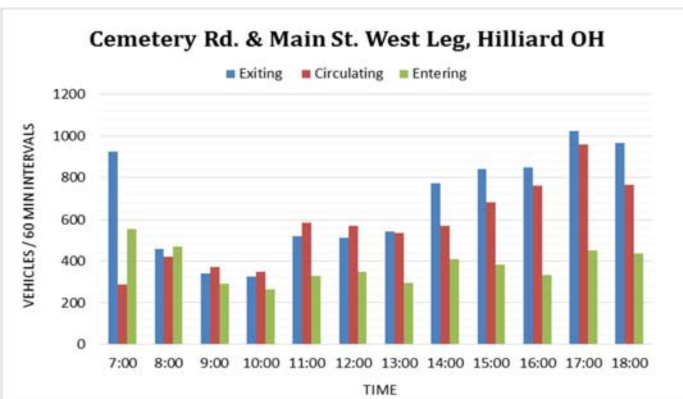


Exhibit 2: Special Feature

Site Background

This roundabout has two-lane entries and exits at all approaches and is outfitted with in-road yield-to-pedestrian warning signs. The east approach features an offset exit leg, while the west approach has more standard crosswalk geometry. The east approach further has overhead flashing beacons for a school crossing, but these devices were not active during the study.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (E Entry)

Studied May 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Hilliard, OH	East Entry	n=60	1	1.7%	7	12%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Hilliard, OH	East Entry	n=60	21.70	13.36	5.61	38.82	37.42

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
East Entry (n=30)	16.8 (2.4)	13.0	23.0	19.0

Exhibit 6: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Utilization Rate	Crossable Gap Utilization Rate
East Entry	57.97%	35.83%	14.42%	93.33%

Exhibit 7: Yielding Rate

Approach	Entry/Exit	Blind/Sighted	Yield Rate
East	Entry	Blind (n=25)	55%
		Sighted (n=25)	25%

Key Observations

- A high school was located at the north-west corner of the roundabout.
- Traffic pattern and driving behavior was different during morning, mid-day and evening, slower, more cautious traffic during morning and aggressive droving during peak hour and evening.
- West leg both entry and exit resulted in high rate of intervention and risky events.
- The roundabout was located in a vicinity of another roundabout.
- The roundabout has a history of failure to yield at entry and high crash rate (mostly PDOs).
- The roundabout get very congestion during afternoon/evening peak hour.
- Lane drops upstream and downstream of the roundabout and an inefficient signal.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (E Exit)

Studied May 2014

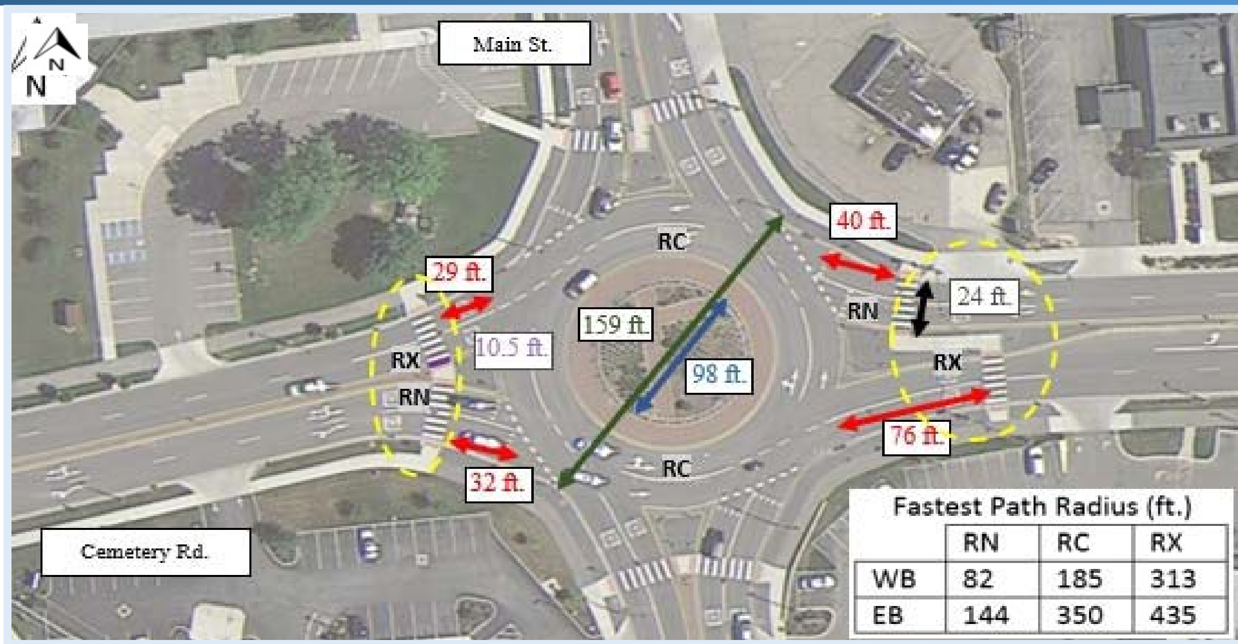


Exhibit 1: Traffic Volumes

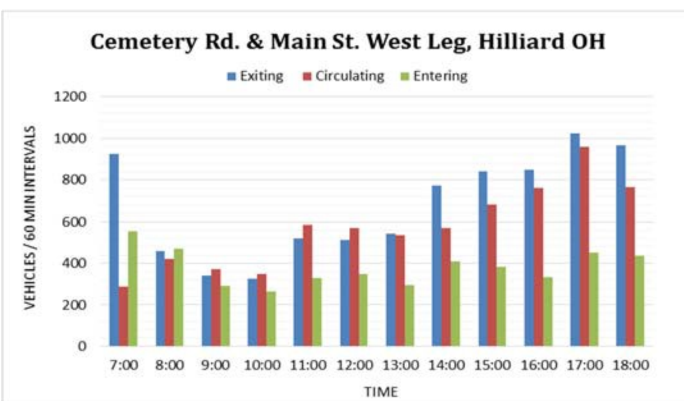


Exhibit 2: Special Feature

Site Background

This roundabout has two-lane entries and exits at all approaches and is outfitted with in-road yield-to-pedestrian warning signs. The east approach features an offset exit leg, while the west approach has more standard crosswalk geometry. The east approach further has overhead flashing beacons for a school crossing, but these devices were not active during the study.

RBT - Hilliard, Ohio – Cemetery Road and Main Street (E Exit)

Studied May 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Hilliard, OH	East Exit	n=60	4	6.7%	7	12%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Hilliard, OH	East Exit	n=60	17.41	10.52	6.07	35.84	24.09

Exhibit 5: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
East Exit (n=30)	25.5 (3.9)	18.0	35.0	29.7

Exhibit 6: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Utilization Rate	Crossable Gap Utilization Rate
East Exit	23.44%	44.90%	19.30%	81.82%

Exhibit 7: Yielding Rate

Approach	Entry/Exit	Blind/Sighted	Yield Rate
East	Exit	Blind (n=25)	56%
		Sighted (n=25)	55%

Key Observations

- A high school was located at the north-west corner of the roundabout.
- Traffic pattern and driving behavior was different during morning, mid-day and evening, slower, more cautious traffic during morning and aggressive droving during peak hour and evening.
- West leg both entry and exit resulted in high rate of intervention and risky events.
- The roundabout was located in a vicinity of another roundabout.
- The roundabout has a history of failure to yield at entry and high crash rate (mostly PDOs).
- The roundabout get very congestion during afternoon/evening peak hour.
- Lane drops upstream and downstream of the roundabout and an inefficient signal located downstream are a few of the causes of gridlock.

RBT - Novi, Michigan – Maple Road and Farmington Road (S Entry)

Studied August 2014

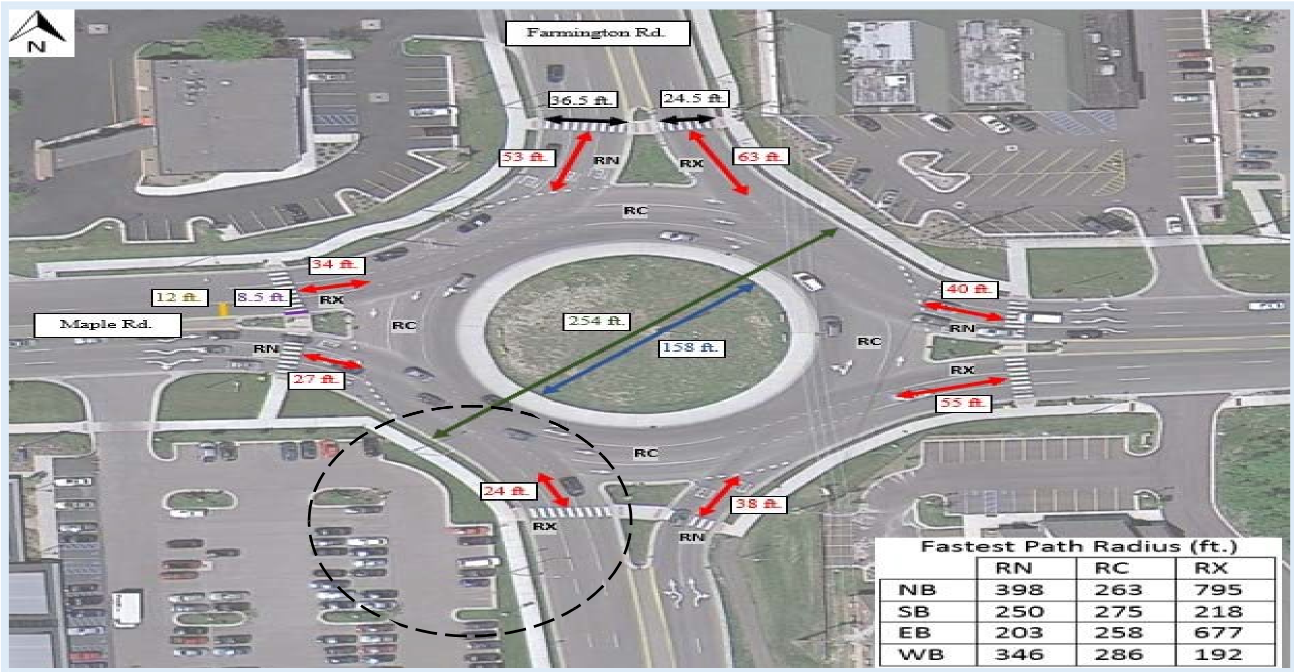


Exhibit 1: Traffic Volumes

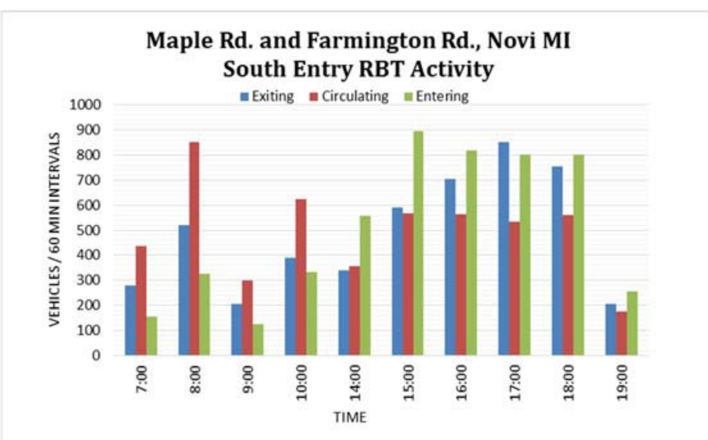


Exhibit 2: Special Feature

Site Background

This multi-lane roundabout is at Maple Road and Farmington Road. The roundabout was previously evaluated in a separate research project in (a) a "before" condition without treatment, and (b) in an "after" condition with Rectangular Rapid-Flashing Beacons (RRFBs) installed. For this study, the roundabout was outfitted also with raised crosswalk at four test legs: 3-lane entry from east, three-lane exit to east, two-lane entry from south, and two-lane exit to north.

RBT - Novi, Michigan – Maple Road and Farmington Road (S Entry)

Studied August 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Novi, MI	South Entry	n=36	0	0%	1	2.78%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Novi, MI	South Entry	n=36	9.30	1.22	7.86	10.67	10.30

Exhibit 5: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
South Entry	65.15%	46.22%	22.73%	100%

Exhibit 6: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
South Entry (n=30)	13(2.7)	9	22	15

Exhibit 7: Yielding Rate

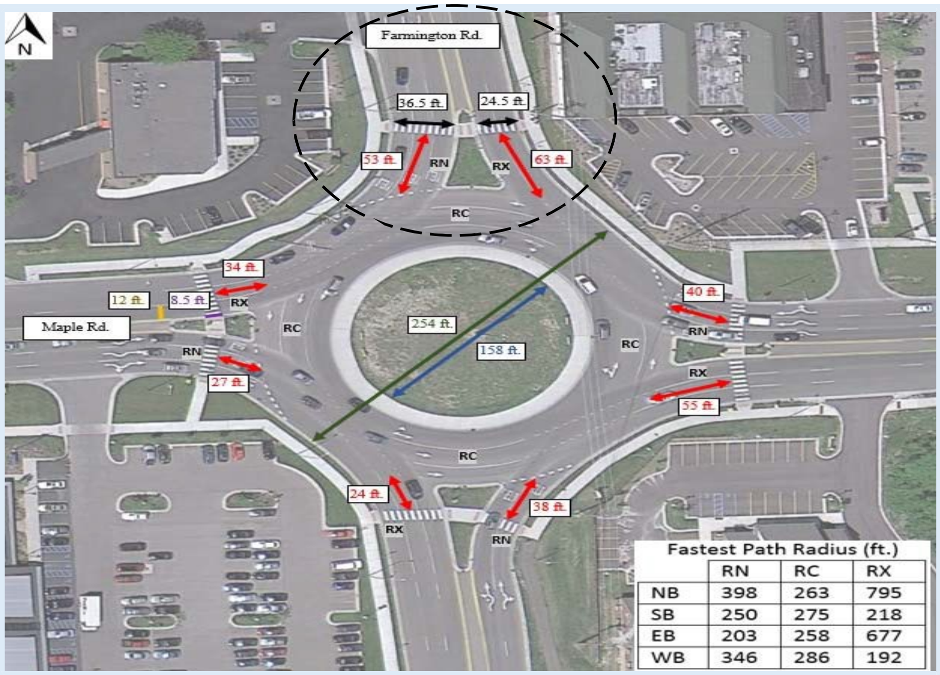
Approach	Exit/Entry	Blind/Sighted	Yield Rate
South	Entry	Blind (n=21)	81%
		Sighted	N/A

Key Observations

- The Raised Crosswalk resulted in significant slowing of vehicles due to a large vertical elevation and steep transition slope.
- The resulting vehicle speeds were very low, which may also have contributed to reasonably high yielding behavior.
- The north exit showed unusually high numbers of interventions, despite being only two lanes across.
- The raised crosswalks resulted in a drastic safety and accessibility improvement over the previous RRFB-only test, but the design of the raised crosswalk resulted in frequent driver frustration.

RBT - Novi, Michigan – Maple Road and Farmington Road (N Exit)

Studied August 2014



	RN	RC	RX
NB	398	263	795
SB	250	275	218
EB	203	258	677
WB	346	286	192

Factor	Rating
Description	
Noise	OK
High exiting volume and ambient noise resulting from heavy east-to-west through traffic, which may have made it difficult to hear exiting traffic.	
Visibility	Concerning
Issue because of cabinets, and because crosswalk is too close to downstream end	
Lane Utilization	Imbalanced
Favoring inside lane, but no queuing	

Exhibit 1: Traffic Volumes

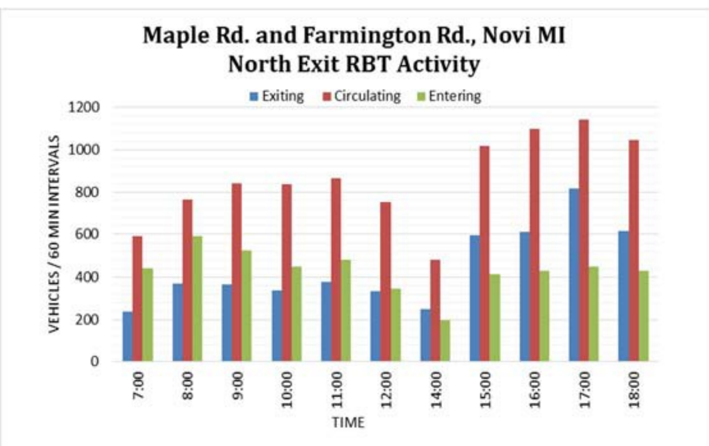


Exhibit 2: Special Feature

Site Background

This multi-lane roundabout is at Maple Road and Farmington Road. The roundabout was previously evaluated in a separate research project in (a) a "before" condition without treatment, and (b) in an "after" condition with Rectangular Rapid-Flashing Beacons (RRFBs) installed. For this study, the roundabout was outfitted also with raised crosswalk at four test legs: 3-lane entry from east, three-lane exit to east, two-lane entry from south, and two-lane exit to north.

RBT - Novi, Michigan – Maple Road and Farmington Road (N Exit)

Studied August 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Novi, MI	North Exit	n=42	3	7.14%	7	16.67%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Novi, MI	North Exit	n=42	8.24	1.52	6.59	10.29	9.61

Exhibit 5: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
North Exit	65.43%	47.17%	26.32%	100%

Exhibit 6: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
North Exit (n=30)	15 (4.6)	9	25	21

Exhibit 7: Yielding Rate

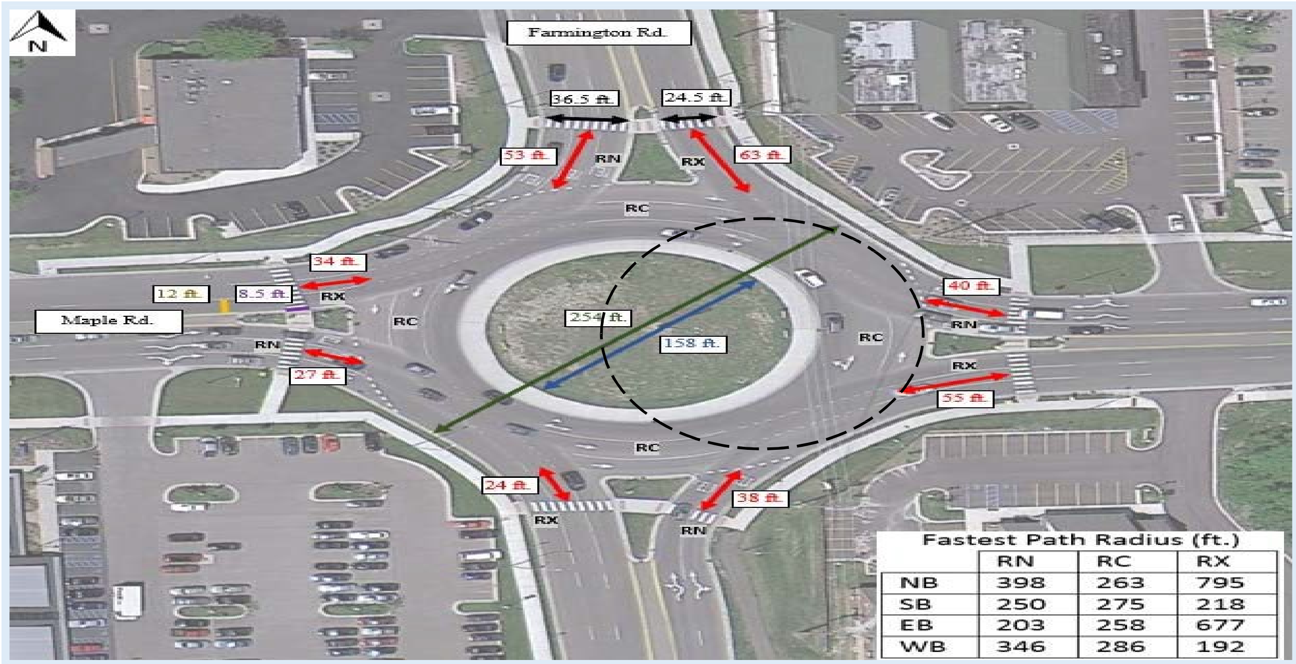
Approach	Exit/Entry	Blind/Sighted	Yield Rate
North	Exit	Blind	N/A
		Sighted (n=15)	67%

Key Observations

- The Raised Crosswalk resulted in significant slowing of vehicles due to a large vertical elevation and steep transition slope.
- The resulting vehicle speeds were very low, which may also have contributed to reasonably high yielding behavior.
- The north exit showed unusually high numbers of interventions, despite being only two lanes across.
- The raised crosswalks resulted in a drastic safety and accessibility improvement over the previous RRFB-only test, but the design of the raised crosswalk resulted in frequent driver frustration.

RBT - Novi, Michigan – Maple Road and Farmington Road (E Entry)

Studied August 2014



	RN	RC	RX
NB	398	263	795
SB	250	275	218
EB	203	258	677
WB	346	286	192

Exhibit 1: Traffic Volumes

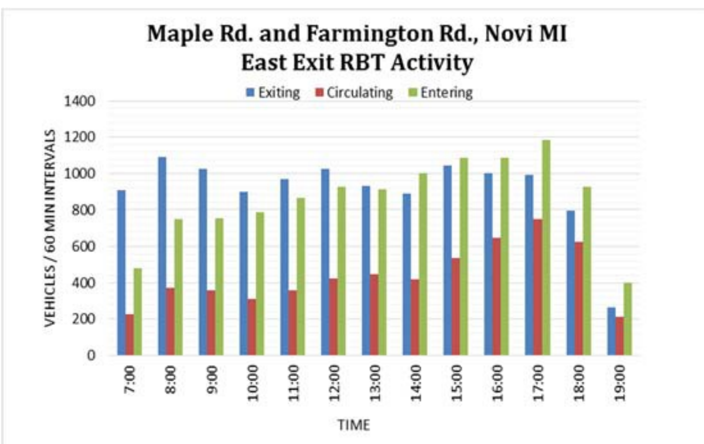


Exhibit 2: Special Feature

Site Background

This multi-lane roundabout is at Maple Road and Farmington Road. The roundabout was previously evaluated in a separate research project in (a) a "before" condition without treatment, and (b) in an "after" condition with Rectangular Rapid-Flashing Beacons (RRFBs) installed. For this study, the roundabout was outfitted also with raised crosswalk at four test legs: 3-lane entry from east, three-lane exit to east, two-lane entry from south, and two-lane exit to north.

RBT - Novi, Michigan – Maple Road and Farmington Road (E Entry)

Studied August 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Novi, MI	East Entry	n=31	0	0%	2	6.45%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Novi, MI	East Entry	n=31	9.35	2.86	5.37	12.09	11.33

Exhibit 5: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
East Entry	90.77%	42.37%	26.67%	100%

Exhibit 6: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
East Entry (n=30)	13 (2.2)	9	18	15

Exhibit 7: Yielding Rate

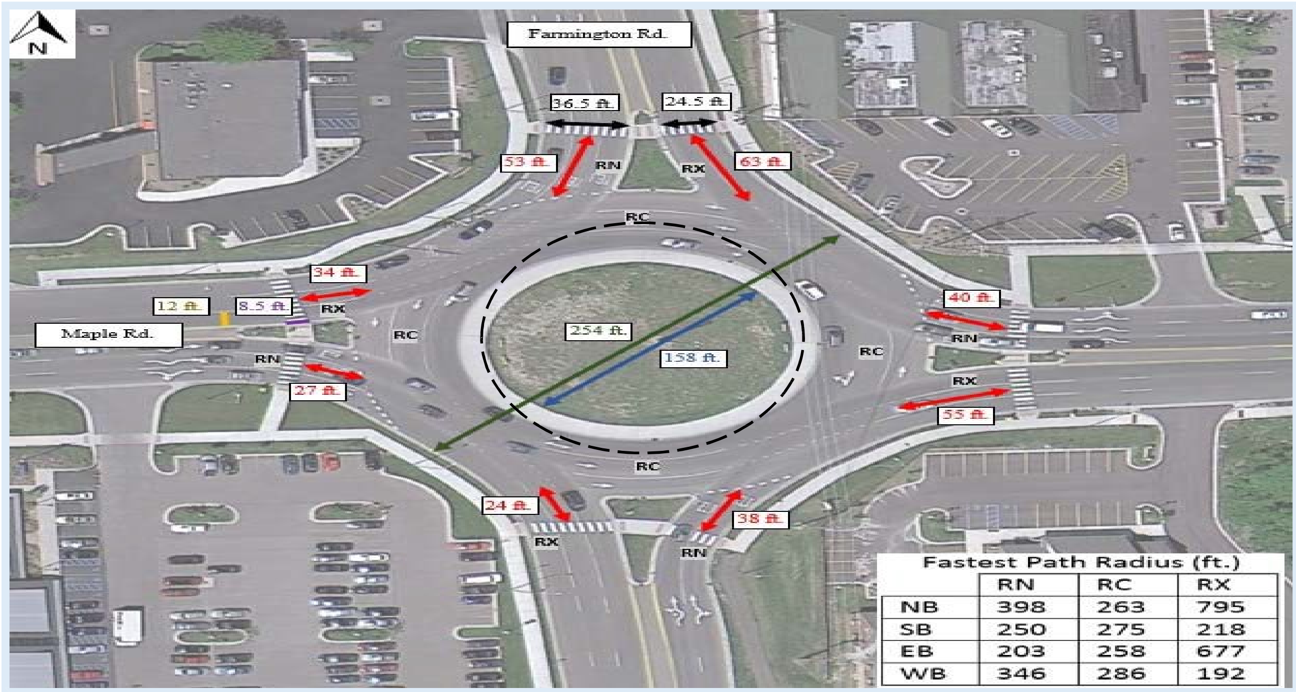
Approach	Exit/Entry	Blind/Sighted	Yield Rate
East	Entry	Blind (n=20)	55%
		Sighted (n=15)	93%

Key Observations

- The Raised Crosswalk resulted in significant slowing of vehicles due to a large vertical elevation and steep transition slope.
- The resulting vehicle speeds were very low, which may also have contributed to reasonably high yielding behavior.
- The north exit showed unusually high numbers of interventions, despite being only two lanes across.
- The raised crosswalks resulted in a drastic safety and accessibility improvement over the previous RRFB-only test, but the design of the raised crosswalk resulted in frequent driver frustration.

RBT - Novi, Michigan – Maple Road and Farmington Road (E Exit)

Studied August 2014



	RN	RC	RX
NB	398	263	795
SB	250	275	218
EB	203	258	677
WB	346	286	192

Exhibit 1: Traffic Volumes

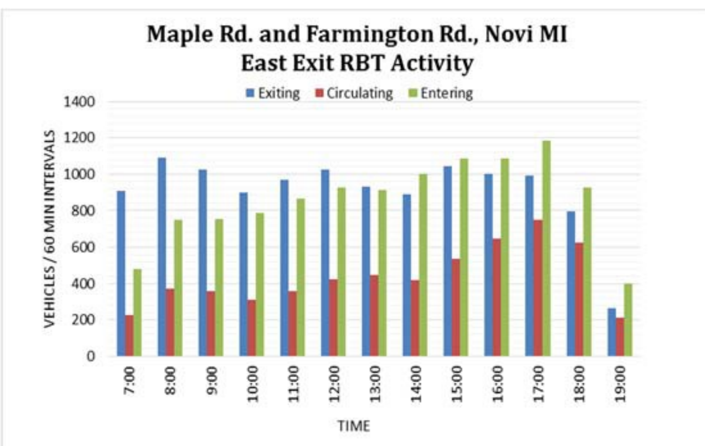


Exhibit 2: Special Feature

Site Background

This multi-lane roundabout is at Maple Road and Farmington Road. The roundabout was previously evaluated in a separate research project in (a) a "before" condition without treatment, and (b) in an "after" condition with Rectangular Rapid-Flashing Beacons (RRFBs) installed. For this study, the roundabout was outfitted also with raised crosswalk at four test legs: 3-lane entry from east, three-lane exit to east, two-lane entry from south, and two-lane exit to north.

RBT - Novi, Michigan – Maple Road and Farmington Road (E Exit)

Studied August 2014

Exhibit 3: O&M Estimated Intervention and Risky Events

O&M and Observer Interventions			O&M Estimated Interventions		O&M Estimated Risky Events	
			Count	Rate	Count	Rate
Novi, MI	East Exit	n=32	0	0%	4	12.50%

Exhibit 4: Delay Values

Average Delay (sec.)		Count	Ave.	St. Dev.	Min	Max	85%
Novi, MI	East Exit	n=32	10.85	4.25	8.61	17.22	13.48

Exhibit 5: Yield and Gap Rates

Approach	Yield Rate	Yield Utilization Rate	Crossable Gap Rate	Crossable Gap Utilization Rate
East Exit	54.05%	47.50%	25.00%	81.82%

Exhibit 6: Free-Flow Speed Statistics

Location	Avg. (St. Dev)	Min	Max	85%
East Exit (n=30)	15 (3.9)	9	22	20

Exhibit 7: Yielding Rate

Approach	Exit/Entry	Blind/Sighted	Yield Rate
East	Exit	Blind (n=20)	50%
		Sighted (n=16)	38%

Key Observations

- The Raised Crosswalk resulted in significant slowing of vehicles due to a large vertical elevation and steep transition slope.
- The resulting vehicle speeds were very low, which may also have contributed to reasonably high yielding behavior.
- The north exit showed unusually high numbers of interventions, despite being only two lanes across.
- The raised crosswalks resulted in a drastic safety and accessibility improvement over the previous RRFB-only test, but the design of the raised crosswalk resulted in frequent driver frustration.

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