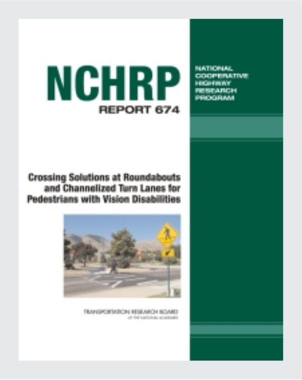

Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 674

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TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
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FOREWORD

By S. A. Parker
Staff Officer
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Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities is intended to provide practitioners with useful information related to establishing safe crossings at roundabouts and channelized turn lanes for pedestrians with vision disabilities. The specific focus areas of the report provide guidance on:

- Identifying under what conditions pedestrians with vision disabilities may experience problems with crossing performance,
- Tying treatment solutions to specific crossing challenges faced by the visually impaired pedestrian population,
- Conducting pedestrian/vehicle studies that help identify performance problems and appropriate treatment strategies,
- Quantifying pedestrian accessibility at a particular crossing,
- Presenting findings from selective field studies performed through this research,
- Developing approaches for extending research findings to other locations, and
- Discussing implications for the practitioner in terms of treatment selection and facility design.

The results of this research will be useful to engineers, the accessibility community, policy makers, and the general public to aid in understanding the specific challenges experienced at these facilities by pedestrians with vision disabilities. It is only through the understanding of the components of the crossing task and the particular challenges involved that solutions can be developed, installed, and evaluated appropriately.

This report is not intended to provide practitioners with requirements of when to install specific treatments, which is a policy decision. Instead, the report provides useful information on the concept of accessibility and how to provide improved crossing environments based on the pedestrian crossing task at hand. The research results also serve to introduce a structured and measurable framework for quantifying the chief operational parameters of accessibility and to establish decision-support through empirical research results.

Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities was prepared under NCHRP Project 3-78A by the Institute for Transportation Research and Education at North Carolina State University, Western Michigan University, Accessible Design for the Blind, and Kittelson and Associates, Inc.

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Many individuals contributed to this research effort. Ronald G. Hughes, Ph.D., of the Institute for Transportation Research and Education (ITRE) at North Carolina State University (NCSU) served as the principal investigator. He was assisted by ITRE director Nagui M. Rouphail, Ph.D., and researchers Christopher M. Cunningham and Bastian J. Schroeder, Ph.D. Also at ITRE, graduate student Katy S. Salamati and undergraduate students Hunter M. Brown and Brian S. Statler assisted in the reduction and analysis of video data. The ITRE team worked closely with subcontractors at the Western Michigan University Department for Blind and Low Vision Studies, at Accessible Design for the Blind, and at Kittelson and Associates, Inc. Researchers at Western Michigan University included Richard Long, Ph.D., David Guth, Ph.D., Robert Wall Emerson, Ph.D., Dae Kim, Ph.D., and Paul Ponchilla, Ph.D. Researchers at Accessible Design for the Blind were Janet Barlow and Billie Louise (Beezy) Bentzen, Ph.D. Researchers at Kittelson and Associates, Inc., included Lee Rodegerdts, Ed Myers, Erin Ferguson, Justin Bansen, Cade Braud, and Pete Jenior. All subcontractors made significant contributions throughout this project. Early in the project, the team further worked with researchers at the Midwest Research Institute and at the Highway Safety Research Center and is grateful for the contributions of these individuals. Throughout the project the team further received valuable input from Daniel Ashmead, Ph.D., of Vanderbilt University and Duane Geruschat, Ph.D., of Johns Hopkins University.

The authors would like to express their gratitude for research partners in the various municipalities where data collection took place through this project. In particular, the team would like to thank Dan Hartman and Vince Auriemma of the town of Golden, CO, and Elizabeth Babson, Charlie Jones, and Scott Lamont with the city of Charlotte, NC. The team would also like to thank a number of people who assisted with the installation and programming of various crossing treatments tested through this project, including Mr. Richard Nassi from the city of Tucson, AZ, John McGaffey and Lynn Mack at Polara Engineering, and WL Contractors in Golden, CO.

Special thanks go to all participants for completing challenging crossings and for providing frank opinions about observed issues at the test locations. The authors would also like to thank several individuals who have been invaluable in recruiting participants for this research, including Trian Boyd-Pratt of Aurora, CO, and Ajqcquelyn A. Jaikins, Alice Galvan, and Laura Park-Leach of the Metrolina Association for the Blind in Charlotte, NC.

The authors especially thank the NCHRP Project 3-78A panel members for diligent service in guiding this multi-year project and in providing thorough and pertinent reviews of interim and final project deliverables.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SUMMARY

Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities

This report explores concerns over the accessibility of two complex intersection forms for pedestrians who are blind: intersections with channelized right turn lanes and modern roundabouts with one-lane and two-lane approaches. Based on the findings of this research project, significant impediments to the accessibility of these sites exist for pedestrians who are blind, but some crossing solutions can increase the accessibility in terms of improving safety and reducing delay. The following sections summarize the research approach and major conclusions of this study.

Project Overview

Objectives

The guidance in this report is intended to provide practitioners with useful information related to establishing safe crossings at roundabouts and channelized turn lanes (CTLs) for pedestrians who are blind. The specific objectives of this project were to:

- Identify and field test crossing treatments with the potential to enhance accessibility for pedestrians who are blind,
- Formulate and apply an evaluation framework and associated performance measures that can quantify accessibility,
- Develop approaches to extend the findings to other sites through statistical modeling and microsimulation, and
- Discuss implications of the results for engineering practice and the ongoing accessibility debate.

This report is not intended to provide practitioners with rigid requirements of when to install specific treatments. To do so would involve policy decisions that are beyond the scope of this effort. Instead, the report provides pertinent information on the concept of accessibility and how to provide improved crossing environments based on the crossing task for a visually impaired pedestrian.

Problem Definition

The crossing task for blind pedestrians consists of four principal tasks that need to be mastered to successfully cross the street:

1. *Finding the crosswalk* and identifying the intended crossing location at an unknown intersection,

2. *Aligning to cross* to establish a correct initial heading at a crosswalk that may or may not be aligned perpendicular with the sidewalk,
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, and
4. *Maintaining alignment while crossing* multiple lanes over the length of the entire crosswalk until the far side of the roadway is reached.

The crossing task at channelized right turn lanes and modern roundabouts is challenging due to the prevailing curved vehicle trajectories and complicated by the absence of a pedestrian signal at most crossings. While many pedestrian crossings are unsignalized, traffic patterns at a conventional orthogonal intersection are more readily interpreted by a blind traveler. At pedestrian crossings with signals, the presence of an accessible pedestrian signal (APS) can provide further information to a blind traveler about the present signal phase and the anticipated traffic patterns. At the crosswalks studied in this research, no signals were present (in the base condition), which resulted in a largely uninterrupted flow of traffic. The geometric configuration of the intersection can further result in elevated speeds at the crosswalk, and busy traffic volumes can contribute to high ambient noise levels, further complicating the task of correctly identifying vehicle trajectories based on auditory information alone. Various prior research efforts have documented the crossing challenges for pedestrians who are blind at roundabouts and intersections with channelized turn lanes, and these findings have been confirmed in this project.

Research Approach

Site and Treatment Selection

The NCHRP Project 3-78A research effort was focused on the evaluation of infrastructure-based treatments that are within the jurisdiction of a public agency. Other agent-based treatments that may be carried out by the pedestrian were considered to be outside the scope of this effort. The project began with an extensive list of infrastructure-based treatments that was narrowed down through an internal team survey process to a small subset of treatments, that were deemed to have the greatest chance for success and that had not previously been evaluated through research. The list of treatments conceptually falls along a two-dimensional performance assessment matrix:

1. The *degree of control* over critical pedestrian and driver behaviors, and
2. The *costs* for acquisition, installation, and maintenance by an agency.

The research team carefully matched the degree of control to the expected crossing challenges at a test location, while striving to minimize agency cost. As a result, a two-lane roundabout crossing was outfitted with a signalization device and speed-reducing traffic calming features while a single-lane channelized turn lane was outfitted with flashing beacons and sound-amplifying pavement treatments. The number of treatment field installations was constrained by the team's ability to identify agencies willing to install and incur the treatment costs. Additional treatments that were not formally installed and evaluated are discussed throughout the report and appendices. (Appendix B through Appendix N are contained in *NCHRP Web-Only Document 160,* available on the TRB website.)

Test sites were selected on the basis of representative geometry of roundabout and channelized turn lane designs, the provision of pedestrian facilities, the existence of a sufficiently large pool of blind study participants, and ultimately the willingness of the local road agency to support the research team in treatment installation and evaluation.

Study Design

This research employed a pre–post within-subject experimental design where the same blind study participants conducted crossings in both a pretest before and a posttest after treatment installation. In each treatment instance, a period of several weeks elapsed between treatment installation and conducting of the posttest data collection. This was to permit drivers to acclimate to the presence of the treatment. The within-subject experimental design optimized the statistical power of the analysis, which was critical given the high degree of within- and between-subject variability inherent in the crossing task.

During the experiments, blind participants were familiarized with the intersection geometry and traffic patterns by a certified orientation and mobility (O&M) specialist, who also accompanied the participants during all crossing trials. Subjects were instructed to cross when ready and were not prompted by the O&M instructor as to when to do so. Participants were thoroughly briefed on all aspects of the study. Each participant provided his/her signed informed consent prior to the study. All aspects of the study were reviewed and approved by the Institutional Review Board (IRB) of Western Michigan University as well as a National Academy of Science (NAS) Institutional Review Board.

Analysis Framework

A critical contribution of this research project was the formulation and application of an analysis framework that could be used to quantitatively describe the crossing performance of individual pedestrians as well as to quantify the accessibility impacts of the tested crossing treatments. The analysis framework devised by this project identifies four distinct criteria, which in isolation describe specific components of the crossing task, and which in combination provide an operational assessment of the accessibility of a site.

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?

The interpretations of the italicized terms (*sufficient, reasonable,* and *significant*) in the analysis framework are discussed, but are ultimately subject to policy considerations. This report presents more detailed definitions of what constitutes a yield or crossable gap and offers discussion on how varying levels of delay and safety performance may be interpreted. The research team makes no claim that the current empirical framework for what is considered to be accessible is the final answer to this question. It does, however, represent a framework that was consistently applied to the evaluation of the crossing performances generated by these treatments and to the simulation and statistical modeling based upon these crossing data. And equally important, it represents a measurement and data collection approach that can be carried out by current practitioners and future researchers in the field.

Field Study Results

The empirical field studies were performed at two signalized intersection approaches with channelized right turn lanes, at three single-lane roundabouts, and at two multilane roundabout approaches. The results are reported separately by facility type.

Channelized Turn Lanes

This research provided evidence that channelized turn lane locations can be very challenging to cross for a blind pedestrian. While the mainline crossing locations at signalized intersections often have pedestrian signals supplemented with APS, the channelized right turn lanes are typically not signalized. Turning speeds in channelized lanes are a function of the facility design and often can approach 20–30 mph at the crosswalk. At the same time, driver attention is often diverted to the task of looking for gaps in the cross-street traffic in preparation for the downstream merge task. Observations at the test locations gave evidence that yielding behavior was very low, in the range of 15%, and that driver speeds were higher during signal phases where no conflicting downstream traffic was expected. Given the frequency of these types of facilities across the United States, the research team has identified a concern for accessibility that may even go beyond that of the (presently less frequent) roundabout installations. More research is strongly recommended in this area to work toward national accessibility guidelines for channelized turn lanes.

At the tested location, the pretest pedestrian performance measures were characterized by mean pedestrian delays of 25 s to cross the single lane of traffic. The 85th percentile delay was 40 s. The crossing was further characterized by high risk. On average, the accompanying O&M instructor had to intervene (i.e., pull back the blind participant) during 5.6% and 9.4% of the crossings at the two CTL locations, respectively. These interventions took place when the O&M instructor perceived there to be a high risk of a pedestrian–vehicle collision.

In addition to high speeds and low yielding rates on the order of 15% to 18%, the crossing difficulty was attributed to high ambient noise levels from adjacent traffic at the main intersection and a difficulty to discern turning vehicles from through traffic.

The CTL crossing treatments included a *pedestrian-actuated, flashing-yellow beacon* and *on-pavement sound strips* that resulted in an audible "clack" noise when traversed by a turn-lane vehicle. The beacons were intended to increase driver yielding, while the sound strips were intended to improve the audible information of turning-versus-through vehicles. The evenly spaced sound strips further sent different sound patterns for a vehicle traveling at constant speed compared to one that was decelerating in potential preparation for a yield. The sound strips were tested in isolation as well as in combination with the beacon. The results showed that the sound strip in isolation resulted in a significant decrease in O&M interventions, from 9.4% to 2.9%. A light reduction in average delay from 26.2 s to 18.5 s was not statistically significant. The combination beacon and sound-strip treatments significantly reduced O&M interventions from 5.6% to 1.4% and decreased overall pedestrian crossing delay from an average 23.4 s to 12.2 s to cross one lane of traffic. The treatment effect was attributed to a slight increase in driver yielding (15.2% to 22.0%), but mostly to an increased rate of utilization of yield and gap crossing opportunities. The interventions observed following installation of the treatments suggest that risky pedestrian crossings were not totally eliminated by the installation of the pedestrian-actuated flashers and/or the surface-mounted sound-strip treatments. It could therefore be argued that accessibility was improved but not totally achieved with these CTL treatments.

The team concludes that signalized treatments may need to be considered at channelized turn-lane sites, where the combination of high traffic volumes and speeds results in a risky and high-delay crossing environment. While no low-volume and low-speed turn lanes were tested, the team recommends that the sound strip and beacon treatment combination be further evaluated at other locations due to its low cost and degree of control. Since field tests suggested that high vehicle speeds contributed to the high incidence of unsafe crossings at the tested location, geometric designs and treatments intended to reduce vehicular speed, such as traffic calming designs, raised crosswalks, pork-chop island design, narrow lane width, small curve radii, and the absence of an acceleration lane may further decrease the likelihood of unsafe crossing judgment by pedestrians who are blind. In short, there are a number of yet-to-be-researched CTL treatments that have the potential to improve CTL accessibility.

Single-Lane Roundabouts

This research concludes that while some blind research participants had difficulties crossing single-lane roundabouts in a safe manner, these sites appear not to pose crossing difficulties that are beyond those experienced by many blind travelers at similar signalized intersections. The accessibility of single-lane roundabouts seems to be critically linked to:

- Low vehicle speeds at the crosswalk, where reduced vehicle speeds are the result of good geometric design as opposed to driver willingness to reduce speeds due to the possibility of encountering a pedestrian;
- The willingness of a majority of drivers to yield to pedestrians;
- Properly installed detectable warning surfaces at all transition points between sidewalk and the street, including the pedestrian splitter island; and
- Availability of O&M instruction customized to roundabout crossings to explain to pedestrians the intersection geometry and the expected traffic patterns at the crossing.

Field studies performed as part of this project evaluated three single-lane roundabouts with varying geometries and traffic volumes. At two of the three roundabouts, the majority of blind participants were able to identify and utilize crossing opportunities within approximately 11 s of average delay per pedestrian for crossing one leg of the roundabout (entry or exit). At the third single-lane roundabout, average delay was 25 s, with many blind participants experiencing even longer delays to cross one lane of traffic. Interestingly, this high-delay roundabout was characterized by low traffic volumes (9,900 vehicles per day) and low yielding rates (approximately 6%), which resulted in pedestrians waiting for “all-quiet” periods to cross. The rate of O&M interventions at this low volume roundabout was also low at 0.8%.

A slightly higher intervention rate (1.4%) was observed at one of the other, lower-delay, single-lane roundabouts. At the third single-lane roundabout, the rate of interventions was 3.9%, which raises concerns that some attributes of single-lane roundabouts decrease accessibility. Traffic volumes at this roundabout were higher (more than 15,000 vehicles per day), but a yielding rate of 33% resulted in a relatively low average delay of around 11 s per pedestrian per leg.

There were some blind travelers at all three single-lane roundabouts, however, who experienced higher delays in crossing (up to an average 74 s per leg over all crossing attempts) and some who experienced higher than average intervention rates. The research team was directed by the study panel to not evaluate any treatments at single-lane roundabouts.

There remains concern over the accessibility of single-lane roundabouts with vehicle speeds higher than those observed at the data collection sites, with higher traffic volumes, and with a lower likelihood of drivers yielding to pedestrians. Future research should target such sites and investigate treatments that are geared towards reducing speeds and increasing yielding behavior.

Two-Lane Roundabouts

This research confirmed that two-lane roundabouts are challenging and not accessible without the provision of additional crossing treatments or without a drastic change toward an increase in likelihood of drivers voluntarily yielding to pedestrians. The crossing difficulties are attributed to generally higher speeds and traffic volumes compared to single-lane facilities. Higher driver speeds appear to be inversely related to the likelihood of drivers yielding to pedestrians, and are further associated with a higher risk of pedestrian injury in the event of a collision. Multilane crossings further carry the added risk of multiple-threat situations, where a yielding vehicle in the near lane may visually and auditorily mask the presence of a vehicle in the far lane, relative to the position of the waiting pedestrian.

Prior to treatment installation, the two-lane roundabout in this study showed average O&M intervention rates on the order of 2.4% to 2.8% of crossings and average delays of 16 to 17 s to cross just one of the two legs (entry or exit) of the roundabout. While these statistics shouldn't be generalized across all two-lane roundabouts, the team believes that the crossing performance could be even worse at higher-volume facilities and at roundabouts with three-lane approaches, which should be the focus of future research.

Two treatments were tested at the two-lane roundabout location, both of which resulted in notable improvements over the pretest condition. The tested treatments were a *pedestrian hybrid beacon* (PHB, also known as a HAWK signal) and a *raised crosswalk*. Both resulted in statistically significant decreases in pedestrian delay and crossing risk at the test locations. The raised crosswalk treatment reduced average pedestrian delay from 17.0 s to 8.0 s. The PHB reduced delay from 16.0 s to 5.8 s on average for crossing two lanes of traffic. The intervention rates at the two studied crosswalks dropped from 2.8% of trials and 2.4% of trials prior to installation to zero after installation of each of these treatments. The team concludes that without treatment in place, pedestrians who are blind may be exposed to an unacceptable level of risk at two-lane roundabouts. It is further concluded that the risk level appeared acceptable after either of the tested treatments was installed at this site and under prevailing (traffic) conditions. It is unclear if and how crossing performance would change with higher traffic volumes or at a site with different geometry.

The team was surprised that the intervention rate for *both* treatments was zero, as it was anticipated that the raised crosswalk would not yield as great a risk reduction as the PHB. Field notes from a team observer indicate that there were eight risky multiple threat crossings at the raised crosswalk that did not actually result in interventions. No such events were recorded at the PHB. Additional research at other locations and with other individuals is necessary to determine whether there is in fact no difference in risk between these two treatments.

Interpretation

Applications to Other Sites

The report presents two approaches for extending the research results to other locations. The first approach is based on statistical modeling of pedestrian delay as a function of behavioral attributes of pedestrians and drivers. The second approach is based on traffic microsimulation, where the same behavioral attributes can be used to simulate different behaviors of pedestrians and drivers. Both approaches are considered preliminary at this point, and a more extensive application is necessary to build confidence in the validity of these approaches.

Pedestrian Delay Models

Separate delay models are developed for single-lane roundabouts, two-lane roundabouts, and channelized turn lanes. All three models use natural-log transformed explanatory variables that predict a decrease in delay with an increase in yielding, the availability of crossable gaps (i.e., less traffic), and the rate of utilization of yield and gap crossing opportunities. The models predict greater delay for channelized turn lanes than for single-lane roundabouts, assuming the same traffic patterns and pedestrian behavior. Similarly, delays are greater at two-lane roundabouts than at the other sites, assuming that traffic patterns and user behavior are fixed.

The resulting delay models are statistically significant and produce good estimates of pedestrian delay that match observed field data. The underlying probability terms can be estimated from field observations for other sites or can be estimated from the technical literature and traffic flow theory concepts. The resulting models allow the analyst to distinguish delay encountered at channelized turn lanes, single-lane roundabouts, and two-lane roundabouts. They further allow the analyst to represent the impact of pedestrian crossing treatments on delay.

Simulation

The NCHRP Project 3-78A analysis framework uses the principles of gap and yield availability, the rate of utilization of both types of crossing opportunities, and other performance measures that quantify the level of delay and risk experienced by a pedestrian. This report illustrates that these measures fit within the realm of microsimulation software, which thus represents a second approach for extending the results of this project beyond the observed sample of sites.

The availability parameters represent characteristics of the traffic stream and are a function of traffic volumes, speed, and driver behavior. The utilization parameters are pedestrian behavior attributes that describe a pedestrian's ability and willingness to cross in a yield or gap situation. These factors represent various inputs into a simulation tool and also become sensitivity parameters that can be used to explore changes in driver behavior, pedestrian skill level, or even the installation of a pedestrian crossing treatment. It is demonstrated in this report that input parameter changes in a simulation model result in the hypothesized effects on pedestrian delay and risk measures.

Additionally, the report presents a detailed evaluation of different pedestrian signalization options for single-lane and two-lane roundabouts that considers various crossing geometries and signal phasing strategies, including a comparison of a traditional pedestrian-actuated signal and the PHB that was also field tested in this research. The analysis showed that the impacts of a roundabout pedestrian signal on vehicle operations can be mitigated by using two-stage phasing, a separation of the exit portion of the crosswalk from the circulating lane, and the use of the PHB phasing strategy.

Policy Implications

The U.S. Access Board Draft Public Rights-of-Way Accessibility Guidelines (PROWAG) specify a pedestrian-actuated signal at two-lane roundabout crosswalks with pedestrian facilities. However, the Americans with Disabilities Act (ADA) allows equivalent facilitation in all implementations of requirements. Consequently, other treatments that provide equivalent accessibility are acceptable. This is to allow for improvements in technology, developments in materials or research, or the implementation of new ideas and information. It is up to the designer and/or constructing jurisdiction to provide justification for their installation decisions in the case of an ADA complaint. The team believes that there is some confusion in the interpretation of these standards, in that some may fail to recognize the inherent difference in civil rights laws and engineering standards.

While the current draft requirements focus on two-lane crossings at roundabouts and CTLs as well as treatments that provide information about the crosswalk location such as landscaping or barriers, there is still a responsibility to design and build *all* facilities to be "accessible to and usable by" pedestrians with disabilities (DOJ 1990). The data presented in the present work strongly argues against the belief that all single-lane roundabouts are created equal. While one of the studied sites showed generally low delay and risk, a second site had high pedestrian risk, while the third exhibited high delays. There was high inter-participant variability, which makes any broad conclusions about the accessibility of a particular roundabout type difficult. Further, single-lane channelized turn lane crossings proved very challenging to most of the blind study participants, and additional treatments are necessary. The accessibility of this CTL site was not fully established with the low cost and low degree of control treatments tested in this project, and increased attention therefore needs to be given to this access issue in addition to the national attention on the accessibility of roundabout crossings.

Wayfinding Challenges

This research was primarily focused on the aspect of accessibility that is related to the actual decision of when to initialize a crossing. As discussed earlier in this report, the full accessibility of a crossing involves three other critical tasks: (a) the task of locating the crosswalk, (b) the task of aligning to cross, and (c) the task of maintaining alignment during crossing. Several treatments are available that can assist in these important accessibility tasks, and these should be evaluated in future research.

However, even today anecdotal evidence suggests that certain facility design elements and supplementary treatments can be valuable assets to blind travelers. Design elements that help pedestrians locate the crosswalk include landscaping along the curb (except at the crosswalk) and the presence of a curb ramp at the crosswalk. This landscaping also may provide a clue to blind pedestrians that the intersection is a roundabout. The PROWAG and other U.S. Access Board resources provide additional detail on these and other wayfinding and alignment treatments. The reader is encouraged to refer to those references for further information.

Future Research Needs

This report makes specific recommendations for research in continuation of the work of this research project. With the imminent adoption of the PROWAG, it is necessary to further explore crossing solutions for blind travelers and work toward building a sample size of observations that is appropriate for making policy decisions on a national level. Future research is expected to be facilitated by numerous municipalities and agencies that are already taking the initiative and proceeding with treatment installations. This research can capitalize on the momentum of the ongoing national accessibility debate and existing treatment installations and therefore can be performed with much greater efficiency. The specific areas of future research identified in this report are as follows:

1. More testing and treatment evaluation at channelized turn lane sites, with particular emphasis on treatments with a red signal display for drivers, as well as traffic calming treatments that more drastically increase yielding.
2. Additional treatment testing at two-lane roundabouts to increase sample size and build confidence in treatment effectiveness, with emphasis on treatments with a red signal display and more low-cost traffic calming treatments such as raised crosswalks.
3. Supplemental data for single-lane roundabouts to improve our understanding of the relationship of design and traffic volumes to accessibility, and exploration of treatment needs at high-volume and high-speed designs.

4. Development of improved measures to quantify pedestrian risk that provide a more complete picture than O&M interventions
5. Exploration of education and training measures to assist blind travelers in successfully navigating unknown geometries at roundabouts and channelized turn-lane intersections
6. Added focus on the auditory environment at the crosswalk, its relation to vehicular traffic volumes, and its effect on the ability of a blind pedestrian to make sound crossing decisions, with consideration of the increased frequency of quiet and hybrid vehicles in the traffic stream.
7. Evaluation of new roundabout designs, the potential value in relocating pedestrian crosswalks upstream/downstream of the circulatory traffic lane, and the inclusion of effective speed-calming design treatments between the point where traffic exits the roundabout and a downstream pedestrian crossing location.

While the in-depth evaluation with many participants at each site as performed through NCHRP Project 3-78A was necessary to establish relationships at sufficient statistical power, future research may benefit from revised research designs that sacrifice some statistical power for a greater sample size across more test sites. In working toward broadly applicable guidelines for pedestrian accessibility across the United States, research focused on breadth rather than depth should receive higher priority.

CHAPTER 1

Introduction

This report explores concerns about the accessibility of two complex intersection forms to pedestrians who are blind: intersections with channelized turn lanes (CTLs) and modern roundabouts. Crossing challenges for blind pedestrians have been established through research (e.g., Guth et al. 2005, Ashmead et al. 2005, Schroeder et al. 2006) for both types of intersections. The emphasis of this project was on the identification of crossing treatments that can assist blind travelers in accessing these facilities at reasonable risk and with a reasonable amount of delay.

Channelized turn lanes are a very common intersection treatment, intended to allow heavy right-turning movements to bypass an otherwise signalized intersection. Crosswalks at CTLs are oftentimes unsignalized in the United States, and pedestrians are therefore required to make crossing decisions independently, without assistance from an accessible pedestrian signal (APS) or other audible device.

Modern roundabouts are increasingly being adopted by the transportation community in the United States due to their ability to process balanced and unbalanced traffic patterns, their aesthetic appeal, and most importantly, their documented safety benefits (e.g., Rodegerdts et al. 2007, FHWA 2000, Persaud et al. 2000). Similar to CTLs, there remain concerns about the accessibility of modern roundabouts to certain groups in the pedestrian community. Of particular concern is the accessibility to pedestrians with blindness or low vision (U.S. Access Board 2003).

Roundabouts and CTLs, like other unsignalized intersections, present challenges that are different from signalized intersections for individuals with blindness and other visual impairments. Roundabouts have relatively free-flowing traffic patterns, and they lack the more predictable pattern of traffic movement that is associated with signalized intersections. This reduced predictability sometimes makes it difficult to judge when it is safe to cross at roundabout crossings using auditory cues alone. Judging gaps in traffic that afford crossing, or determining that vehicles have yielded just upstream of the crosswalk, can be difficult, particularly when other sounds mask the sounds of approaching or yielded vehicles. Another key challenge for roundabouts and CTLs is that they often carry higher volumes than other typical two-way stopped control (TWSC) and all-way stopped control (AWSC) intersections, which are also unsignalized.

In addition to determining when to cross the road, pedestrians with vision impairments must identify where to cross and which way to walk during the crossing, and must determine when they have arrived at their destination curb or island (Guth et al. 1989). These challenges are common to all pedestrian crossings, but are exacerbated at roundabouts and CTLs due to the unexpected, non-perpendicular alignment of the crosswalk.

While prior research has demonstrated and documented the crossing challenges for blind pedestrians at these facilities (e.g., Guth et al. 2005, Ashmead et al. 2005, Schroeder et al. 2006), it has failed to develop and test crossing solutions that would improve the accessibility of these facilities. The objective of NCHRP Project 3-78A was to fill that void and evaluate a range of pedestrian crossing treatments in controlled field experiments with the goal of providing decision support to engineers and policy makers.

Safety Is Not Synonymous with Access

The underlying premise of this research is that while *safety* and *access* of a facility are related, the two terms are not synonymous. A facility could be considered safe if the crash rate at the facility is low. However, effective access must be judged by the extent to which any individual or group of individuals limits its use of a facility based on a real or perceived belief that the facility is unsafe or extraordinarily difficult to use. The absence of recorded pedestrian crashes, especially those involving older pedestrians, children, or those with visual and/or physical impairments, does not constitute proof that a facility is accessible, nor does the presence of crashes constitute proof that it is inaccessible. Accessibility must be evaluated in terms of direct observation that a facility *can be* used by *all persons,* independent of whether they are actually observed using it. For the question of the accessibility of complex intersections to pedestrians who are blind, a conventional engineering analysis of pedestrian crashes therefore does not provide the necessary information.

Comparing Roundabouts and Channelized Turn Lanes

When attempting to cross a CTL or the entry/exit lane of a roundabout, a blind pedestrian must decide, largely on the basis of auditory cues, when it is safe to cross. Both types of facilities share the following common characteristics with respect to the crossing task for blind pedestrians:

- Use of (typically) unsignalized pedestrian crossings without an audible device that assists in determining signal status,
- Potentially high levels of ambient noise associated with background traffic at the main intersection or roundabout,
- Free-flowing traffic at the exit portion of the roundabout crossing and at non-yield-controlled CTLs,
- Challenge of curved vehicle paths that differ from more standard orthogonal intersections,
- Ambiguity about vehicle trajectories between through/circulating and turning/exiting traffic,
- Lack of information identifying the sites as different from conventional orthogonal intersections, and
- Crossings that originate from a refuge island where traffic moves in front of and behind the pedestrian.

However, the two types of facilities also exhibit some significant differences that need to be emphasized. Through-vehicle (and potentially turning-vehicle) speeds are expected to be higher in the vicinity of a CTL, resulting in an elevated level of background noise and potentially different behavior in terms of drivers yielding to pedestrians. The difficulty of the auditory discrimination at a CTL will be influenced by a number of factors, such as (a) whether the CTL has a dedicated deceleration lane and the length of that lane, (b) whether the CTL has a dedicated acceleration lane and the length of that lane, (c) the radius of the channelized lane and the associated design speed, and (d) whether vehicles exiting the channelized lane are able to merge with traffic with or without any reduction in speed. The last point is principally associated with the presence and length of a downstream acceleration lane.

For roundabout crossings, a range of different roundabout geometries exist that affect the crossing task. Roundabouts vary in the number of approach lanes, the number of circulatory lanes, the inscribed circle diameter, crossing point distance from circulating traffic, and most importantly traffic patterns, including volumes, gap distributions, and vehicle classification.

Scope of Work

The objective of this research was to explore through empirical research geometric designs, traffic control devices, and other treatments that will enable safe crossings at roundabouts and CTLs for pedestrians who are blind. The results of this research also will be useful to engineers, the accessibility community, policy makers, and the general public to aid in understanding the specific challenges experienced by pedestrians who are blind at these facilities. It is only through understanding the components of the crossing task and the particular challenges involved that solutions can be developed, installed, and evaluated appropriately.

The focus of this research was on people who are blind, and therefore the term “blind,” rather than “visually impaired,” will be used throughout this document. In this context, people who are blind are defined as those who have only light-perception or less vision and who are therefore unable to identify traffic patterns, signs, markings, or signal displays. The research clearly has implications for other pedestrians with vision impairments, which includes those with limited or low vision. But all studies performed through this research involved only pedestrians who are blind according to the definition above.

The guidance in this report is intended to provide practitioners with useful information related to establishing safe crossings at roundabouts and CTLs for pedestrians who are blind. The specific focus areas are to provide guidance on:

- Identifying when a pedestrian crossing problem may be present,
- Tying treatment solutions to specific crossing challenges faced by the pedestrian population,
- Conducting pedestrian/vehicle studies that help identify appropriate treatment strategies,
- Quantifying the accessibility performance at a particular crossing,
- Presenting findings from selective field studies performed through this research,
- Developing approaches for extending research findings to other locations, and
- Discussing implications for the practitioner in terms of treatment selection and facility design.

This report is not intended to provide practitioners with requirements of when to install specific treatments, which is a policy decision. Instead, the team provides useful information on the concept of accessibility and how to provide improved crossing environments based on the pedestrian crossing task at hand.

The research results do serve to introduce a structured and measurable framework for quantifying the chief operational parameters of accessibility (Schroeder et al. 2009) and to establish decision support through empirical research results. However, the results do not provide a comprehensive evaluation of all potential treatments and all variations of sites. Such effort is considered well beyond the scope and budget of a single project. The authors do hope, however, that the reader will find the research findings and discussions in this document useful and that the results provide a common baseline for discussion of questions of accessibility at these locations. The establishment of a common language between the engineering, accessibility, and policy communities is an important first step in approaching a common challenge. This report hopes to provide this language.

Content of This Report

The basic outline of this report follows the sequence of study used by the team to conduct the research. After an initial review of the literature and pre-existing knowledge base, the availability of actual treatments is discussed. This includes a process for narrowing down a long list of treatment alternatives to a succinct and well-targeted short list of solutions that maximize the efficiency of limited project resources. Following treatment identification, test sites were selected from a database of sites available for treatment installation. The geometry, traffic volumes, availability of resources (team and municipal), and team judgments based on experience were applied in deciding which locations should be used for treatment installations. Field trials were conducted using a focused experimental design approved by the Institutional Review Board (IRB) of Western Michigan University that used blind study participants at various locations. Field results were analyzed using a newly developed analysis framework that highlights the different aspects of the crossing task and allows for a target's application and evaluation of treatment effects. Finally, the results were interpreted and extended to other applications using statistical modeling and discussion of simulation-based analysis approaches.

The report is organized as follows: After the general introduction in this chapter, Chapter 2 gives an overview of the literature and background information on the question of pedestrian accessibility to complex intersections. Chapter 3 presents a methodology for identifying potential treatment solutions and discusses the data collection approach used in this research. It further presents the process used to select treatment sites and provides narrative descriptions of these locations. Chapter 4 presents an analysis framework for quantifying pedestrian accessibility. This framework guides the analysis in this document and is generally applicable to other studies. Chapter 5 presents the results of the field studies performed under the auspices of this project. Chapter 6 presents efforts to extend the field results to other locations and geometries through statistical modeling and simulation-based analysis approaches. Finally, Chapter 7 presents an interpretation of the results and conclusions of the research effort. The report further contains significant supplemental materials in several appendices. The reader is referred to this supplemental material directly from the discussion in the different chapters. In total, fourteen appendices are provided:

- Appendix A presents detailed analysis results for all field studies conducted through NCHRP Project 3-78A.
- Appendix B provides additional detail on the long list of treatments considered in this research.
- Appendix C provides results of the internal team treatment survey that was used to narrow the initial long list of treatments to a short list of treatments recommended for field testing.
- Appendix D gives details on site selection, including photographs of other locations considered for this research.
- Appendix E presents details on treatment installations and further descriptions of the NCHRP Project 3-78A test sites.
- Appendix F gives specific details on the pedestrian hybrid beacon (PHB) installation at the two-lane roundabout in Golden, CO, including signal timing plans and other timing details.
- Appendix G includes the blank participant survey forms used for participant questionnaires following each study.
- Appendix H presents details on a team-internal-conflict survey of crossing events at the CTL location intended to verify the viability of the orientation and mobility (O&M) intervention safety measure.
- Appendix I presents further details on the simulation analysis framework in the form of a paper presented by members of the research team.
- Appendix J presents details on development of the accessibility measures used in the analysis framework in the form of a paper presented by members of the research team.
- Appendix K presents details on the development of pedestrian delay models in the form of a paper presented by members of the research team.
- Appendix L presents details on a simulation-based evaluation of roundabout signalization treatments in the form of a paper presented by members of the research team.
- Appendix M discusses the use of visualization techniques in NCHRP Project 3-78A in the form of a paper presented by members of the research team.
- Appendix N presents the completed and signed IRB approval forms for this research along with the blank consent forms signed by all participants.

CHAPTER 2

Synthesis of the Literature

Facility Design

Current roundabout and CTL design criteria are presented in documents such as the AASHTO Policy on Geometric Design of Highways and Streets (AASHTO 2004); the *Intersection Channelization Design Guide* (Neuman 1985); the FHWA's *Manual on Uniform Traffic Control Devices* (2009); the AASHTO Guide for Planning, Design, and Operation of Pedestrian Facilities (2004); the FHWA's *Pedestrian Facilities Users Guide* (Zegeer et al. 2002); the FHWA's *Signalized Intersections: Informational Guide* (2004); the FHWA's *Roundabouts: An Informational Guide* (2000); an updated version of the FHWA roundabout guide available as *NCHRP Report 672: Roundabouts: An Informational Guide,* Second Edition (Rodegerdts et al. 2010); and the research results and synthesis to come from NCHRP Project 3-72, "Lane Widths, Channelized Right Turns, and Right-Turn Deceleration Lanes in Urban and Suburban Areas" (Midwest Research Institute 2011), which will be available in 2011. These documents include provisions for determining the placement of crosswalks, signage, and other aspects of roundabout and CTL design. A key issue is that existing designs are intended to accommodate the majority of pedestrians, who have normal vision. Current designs were not developed specifically to support unassisted crossing of streets by pedestrians who are blind.

Geometric Design for Pedestrian Crossings at Roundabouts

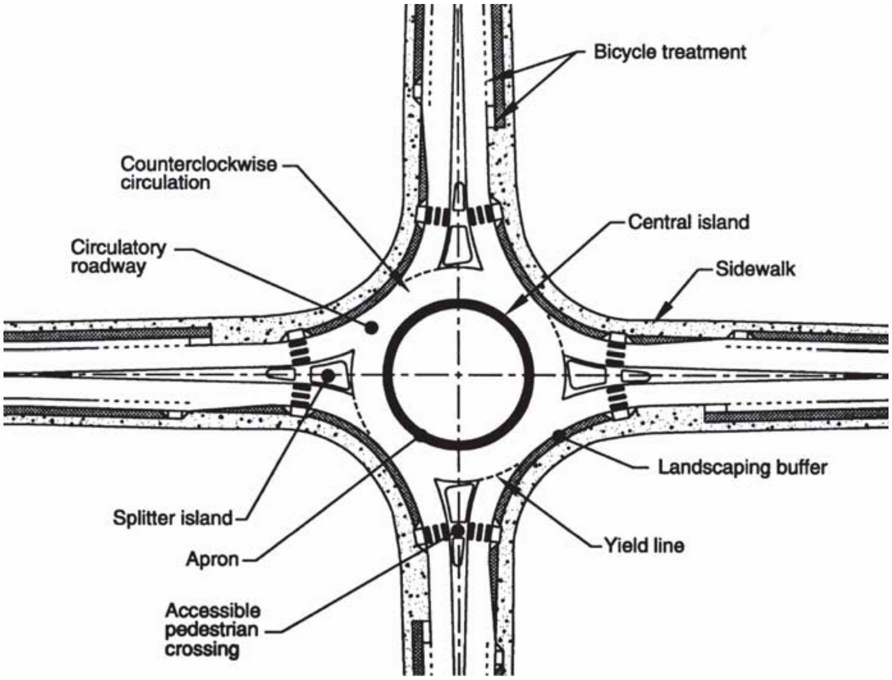
Current practice in the United States (FHWA 2000) locates the pedestrian crosswalk approximately one car length back from the circulating lane, although this varies. The crosswalk is generally perpendicular to the travel lane and passes through an approach splitter island. This island is designed to separate opposing traffic streams, reduce wrong-way movements around the central island, and provide refuge to pedestrians before they cross the second leg of the approach. The presence of the splitter island serves to divide the pedestrian crossing task into two separate segments. Under low traffic volumes, a pedestrian may be able to cross in a single movement. Under higher traffic volumes, pedestrians may wait on the splitter island until a crossable opportunity is detected on the second leg of the crossing. In either case, the pedestrian crossing task is typically focused to one direction at a time. Figure 1 shows a schematic drawing of typical roundabout crosswalk geometry.

The actual alignment of the crosswalk can vary. Often there is no deviation in the orientation of the crosswalk, and the crosswalk proceeds straight from curb to curb. However, some crosswalks are designed with a bend at the splitter island, which may pose wayfinding challenges for blind travelers in the absence of additional tactile cues. There are a few crosswalks that use an offset or zigzag design that deflects pedestrian traffic onto an elongated splitter island before the second part of the crossing. The intent of this treatment is to reinforce two-stage crossing behavior and, to some extent, increase the distance between the crosswalk and the circulating lane.

For all crosswalks, pedestrian ramps at either curb are supposed to be perpendicular to the curb/gutter line. Due to the radius of the curve, they may not be in line with the direction of travel on the crosswalk and therefore may cause alignment difficulties for blind pedestrians. Curb ramps built after 2001 are supposed to have truncated dome detectable warning surfaces at the bottom of the ramp to alert the pedestrian who is blind that he or she has arrived at a street–sidewalk boundary. In the United States, few pedestrian crosswalks at roundabouts are signalized (either for pedestrian or traffic control purposes).

The Geometric Design for Pedestrian Crossings at Channelized Turn Lanes

Channelized turn lanes are much more prevalent in the United States than roundabouts. Despite their increased prevalence, less attention has been given to the effects of treatments



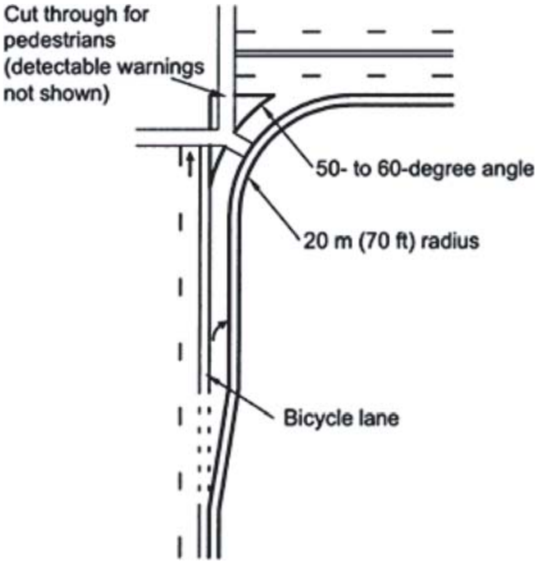
This figure shows a schematic drawing of a roundabout with key features highlighted. The pedestrian crosswalk is placed approximately one car length back from the circulating lane. The entry- and exit-leg portions of the crosswalk are separated by a raised splitter island to provide pedestrian refuge.

Figure 1. Typical roundabout design features and crosswalk geometry (source: FHWA 2000).

designed to improve pedestrian safety and access. In essence, there are three typical locations for a pedestrian crosswalk associated with a CTL. The crosswalk may be located at the upstream (entering) side of the turn lane, at the downstream (or exiting) side, or at the midpoint, perpendicular to the tangent of the curve that defines the turn lane. Figure 2 shows a schematic drawing of a typical CTL with the crosswalk located at the midpoint. The intersection shown has a deceleration lane in the approach of the CTL. This feature may not be present in all designs and can vary in length. Alternate designs may also have an acceleration lane at the downstream end of the CTL (FHWA 2004).

The midpoint crosswalk location presumably minimizes the crossing distance and is likely to coincide with the location of slowest vehicle speeds. When vehicles are stopped for pedestrians, this design provides some degree of storage upstream of the crosswalk before traffic in the through lane is affected.

Upstream crosswalk locations require pedestrians to discriminate between through vehicles and vehicles that intend to turn into the channelized turn lane. This can be difficult, even for sighted pedestrians, since there may be no indication of driver intent until the vehicle is very close to the crosswalk. If it is not possible to discriminate through traffic from turning



This figure shows a schematic drawing of a CTL with key features highlighted. The pedestrian crosswalk is placed at the midpoint of the CTL and approximately one car length back from the downstream merge point.The CTL shows a deceleration lane that allows right-turning traffic to slow down for the turn away from through traffic at the intersection.

Figure 2. Typical CTL crosswalk geometry (source: FHWA 2004).

vehicles, the blind pedestrian must wait until traffic is stopped or until there is no traffic approaching from either direction on the through street.

The downstream crosswalk location creates different issues. At the downstream location, drivers of vehicles in the turn lane are more likely to be looking to their left at vehicles approaching on the major street and not to their right where a pedestrian may be waiting to cross from the curb. Where volumes on the major street are low and gaps required to merge from the turn lane are readily perceived, vehicles may accelerate as they approach the downstream exit, lessening the likelihood that they will yield to pedestrians. However, where volumes on the downstream departure leg are high, there may be times in the signal cycle when vehicles in the channelized lane are regularly stopped to wait for a gap in traffic. Sighted pedestrians often cross between stopped vehicles at these times, but blind pedestrians may have difficulty determining that vehicles have stopped. Higher speeds and lower likelihoods of yielding to pedestrians are also more likely when an acceleration lane is provided at the CTL exit.

Facilities built since 2001 compliant with the American with Disabilities Act (ADA) include a curb ramp with truncated-dome detectable warnings that delineate the edge of the roadway. If the crosswalk and ramp are located upstream or downstream within the CTL, the ramp may terminate into the radius of the curve, which is not perpendicular to the crosswalk. Blind pedestrians may experience problems with identifying the crossing location and alignment at all crosswalks at channelized turn lanes because of the curvature.

Accessibility Challenges

Recent research on the crossing performance of people who are blind at complex intersections demonstrates that there are unique challenges for this population (Ashmead et al. 2005, Guth et al. 2005). Complex intersections, including roundabouts and channelized turn lanes, present some unique challenges for pedestrians with vision impairments. The traffic control strategy at a roundabout entry leg is typically a yield sign, and many drivers are able to enter the circle without the requirement to come to a full stop. Similarly, traffic exiting the roundabout is free-flowing (often accelerating), resulting in largely uninterrupted traffic flow at the exit portion of the crosswalk. Traffic patterns at CTLs are similar in that the right-turning movement is largely free-flowing. Crosswalks at both types of facilities are typically not signalized, and the task of identifying crossing opportunities is thus unassisted. Depending on the geometric design and the location of the crosswalk, vehicle speeds may be relatively high, and the auditory interpretation is complicated because vehicles are moving on a circular path (Ashmead et al. 2005). At signalized intersections, the two traffic streams typically move perpendicularly to each other, presumably making it easier for someone who is blind to interpret directional traffic movements. Finally, the continuous flow of traffic circulating the roundabout can create a difficult auditory environment, and the listening task is complicated by elevated levels of ambient noise.

All of these factors may contribute to accessibility challenges at roundabouts and CTLs. Research in this area and the work of this project have divided the crossing task into four principal areas that guide the understanding of the challenges faced by pedestrians who are blind. Additionally, the four areas require different treatments to improve targeted aspects of pedestrian accessibility. The four crossing components are:

1. Locating the crosswalk,
2. Aligning to cross,
3. Identifying a crossing opportunity, and
4. Maintaining alignment during crossing.

In the following, each component is discussed in detail.

Locating the Crosswalk

A pedestrian approaching an intersection needs to be able to identify the location of the crosswalk. For standard orthogonal intersections, this is a fairly simple task since the curb ramps are located in the vicinity of the corner of the intersection, usually within 15 ft if the turning radius is not significant. However, at roundabouts and CTLs, there is no distinct point of interest (such as the corner) where a pedestrian would expect a crosswalk to be located. Instead, the auditory environment from nonlinear traffic patterns can be difficult to navigate compared to the typical orthogonal intersection.

For roundabouts, finding the crosswalk is highly dependent on the direction of travel and the side of the roundabout being approached. For instance, a pedestrian wishing to turn left with traffic approaching the roundabout from behind her would have the crosswalk on her left, similar to a standard orthogonal intersection. Even so, the circulating traffic does not provide a consistent point of reference to begin looking for the crossing location. The task of walking straight through a roundabout intersection poses further challenges. The pedestrian must be aware that she must navigate around the circle via sidewalk cues or landscaping and then locate the crossing location a significant distance from where the typical crossing would be located at a standard intersection. Since vehicles do not move in a perpendicular fashion with other vehicles, the pedestrian may need repeated attempts to identify the crossing location, which can be time-consuming and dangerous.

For similar reasons, CTLs can be challenging to a blind pedestrian. The unusual geometry associated with the large turning radius does not follow the pattern of a typical intersection. Making the locating task even more difficult is the placement of the crosswalk, which requires crossing an uncontrolled movement at the turn lane. With non-standardized placement of the crosswalk at the upstream end, midpoint, or downstream end, it is difficult to provide blind travelers consistent guidance.

Aligning to Cross

Once the crosswalk has been found, the proper alignment should be determined so that the pedestrian does not start the crossing with an unsuccessful alignment. For instance, many times curb cuts at signalized intersections are installed as a single curb cut in the middle of the curb radius to eliminate the (perceived) need for two perpendicular curb cuts, saving time and costs. This single curb-cut installation method significantly hinders the ability of a blind pedestrian to align correctly. Alignment is an important task that if not done correctly, could lead to problems when maintaining that alignment during crossing. For blind pedestrians, typical aids used for aligning are specialized tactile surfaces or the edge of curb cuts (Barlow et al. 2005). Other research efforts underway at the time of this report [National Institutes of Health (NIH) 2010] are looking at alternative treatments to further aid pedestrians in aligning under various conditions, primarily focused on improving detectable warning surfaces using parallel and perpendicular bar tiles and far-side beacons. At the time of this report, no findings were available on the success or failure of such devices in aligning to cross.

Identifying a Crossing Opportunity

The focal point of this research effort was on measures describing the third component, the task of deciding when it is actually safe to cross conflicting traffic. At unsignalized crossings, which constitute the large majority of roundabouts and CTLs, the two crossing opportunities available to the pedestrian are yielding drivers or large gaps in traffic. At signalized crossings, the pedestrian walk phase presents a planned crossing opportunity that is a function of signal phasing, which can be very useful to a blind pedestrian when negotiating very difficult geometries and traffic conditions such as those posed by large two-lane roundabouts or CTL facilities. However, the walk phase does not ensure that traffic is stopped due to right turns and permissive left-turning movements. Therefore, the walk phase by itself does not identify a safe time to cross.

Maintaining Alignment During Crossing

Finally, the fourth component is the task of maintaining alignment during the crossing, which is greatly facilitated by perpendicular crosswalk geometry. This fourth component depends on the provision of proper aligning geometry (the second component, discussed above) and assistive devices so that the appropriate heading can be properly determined and maintained. In other words, maintaining alignment is highly unlikely if a pedestrian starts the crossing in the unintended direction. Far-side locator beacons or other treatments can be extremely helpful in properly aligning *and* maintaining alignment. Under a separate grant (NIH 2010), research is underway to test alternative alignment devices such as raised guiding surfaces in the pavement area, far-side audible beacons, and remote infrared audible signals. No definitive analysis of such treatments has been completed at this time on the ability of these devices to successfully aid pedestrians in maintaining alignment.

The U.S. Access Board and ADA

One of the responsibilities of the U.S. Access Board is to develop design guidelines for transportation facilities, ensuring that public rights-of-way are accessible to and usable by all people and are thereby in compliance with the ADA. The Access Board published the draft Public Rights-of-Way Accessibility Guidelines (PROWAG, U.S. Access Board 2005), outlining requirements for making crosswalks and intersections in the public rights-of-way compliant with the ADA. Even before the draft PROWAG was published, the requirements for accessibility were outlined in the implementing regulations of Title II of the ADA, which specifies that any newly constructed or altered public facility shall be “readily accessible to and usable by individuals with disabilities” (DOJ 1990), including those with vision loss, mobility impairments, or other disabilities. The draft PROWAG provides more specific guidance, outlining features that make a site compliant with the ADA. Specifically, the provision of a pedestrian-actuated signal with APS at two-lane roundabout approaches is discussed as making the site usable by pedestrians who are blind. A pedestrian-actuated and APS-equipped signal thereby satisfies the accessibility requirement for two-lane roundabout approaches (PROWAG R305.6.2). However, the draft PROWAG continues to allow the use of alternative treatments if justified. The draft PROWAG language for two-lane CTL crosswalks is very similar to two-lane roundabouts in that a pedestrian signal with APS satisfies the accessibility requirement. In addition, the draft PROWAG also specifies the provision of landscaping or barriers to delineate the crossing locations at roundabouts and CTLs, the use of APS devices at all signalized pedestrian crossings, and the provision of detectable warning surfaces on the curb ramp to demark the street–sidewalk boundary (PROWAG R305.6.1). The draft PROWAG does not discuss signalization at single-lane roundabouts or single-lane CTLs.

Pedestrian Signals

Pedestrian crossing control devices can be grouped into two types: pedestrian displays and vehicle displays. Pedestrian displays in the United States typically feature a "Walk" and a "Don't Walk" phase, which operate in either flashing or solid state depending on the phase. Other countries use green and red walking figure symbols instead of the text description. Vehicle displays are further divided into typical green/yellow/red signals that are more commonly used at roadway intersections for vehicular traffic control, and the newer pedestrian hybrid signals (e.g., PHBs) that feature a modified arrangement of vehicle signal displays. The United States and other countries have *warrants* (FHWA 2009) for the installation of pedestrian signals, but the installation of other treatments is less standardized. The pedestrian signal warrants in the United States were initially intended for midblock locations or conventional intersections that would otherwise be stop controlled. A warrant is generally intended to define when a treatment (in this case a signal) is justified. Warrants are not *requirements* to place signals.

Midblock Crossings and Conventional Intersections

In the United States, the *Manual of Uniform Traffic Control Devices* (MUTCD) provides warrants for when traffic signals may be installed (FHWA 2009). There are a total of nine warrants, one of which deals with pedestrians. In the 2009 MUTCD, Warrant 4 (Pedestrian Volume) states that a traffic signal "at an intersection or midblock crossing shall be considered if . . . one of the following criteria is met:

- For each of any 4 hours of an average day, the plotted points representing the vehicles per hour on the major street (total of both approaches) and the corresponding pedestrians per hour crossing the major street (total of all crossings) all fall above the curve in [Figure 3], or
- For 1 hour (any four consecutive 15-minute periods) of an average day, the plotted point representing the vehicles per hour on the major street (total of both approaches) and the corresponding pedestrians per hour crossing the major street (total of all crossings) falls above the curve in [Figure 4]."

Alternatives for the two conditions above are also given for speed limits (posted, statutory, or 85th percentile) that exceed 35 mph or intersections that lie within an isolated community with a population of less than 10,000. The pedestrian volume signal warrant is not to be applied at locations where the distance to the nearest traffic control signal or stop sign is less than 300 ft unless the proposed traffic signal will not restrict the progressive movement of traffic (FHWA 2009).

If one or both of the conditions is met for the pedestrian signal installation, further guidance on placement of the pedestrian traffic signal is provided:

- Traffic signals installed at traditional intersections or major driveways should control the minor street or driveway traffic through actuated means and should include pedestrian detection.
- If the pedestrian signal is installed at a non-intersection location, it should be installed no closer than 30 m (100 ft) from the nearest side street or driveway controlled by stop or yield signs and should also be pedestrian actuated. Recommendations are also provided for adequate sight distance, including removing obstructions within 100 ft of the signal heads on each direction of the approach and equipping with proper signage and pavement markings.
- If the pedestrian signal is installed within a signal system, the traffic control signal should be coordinated appropriately.

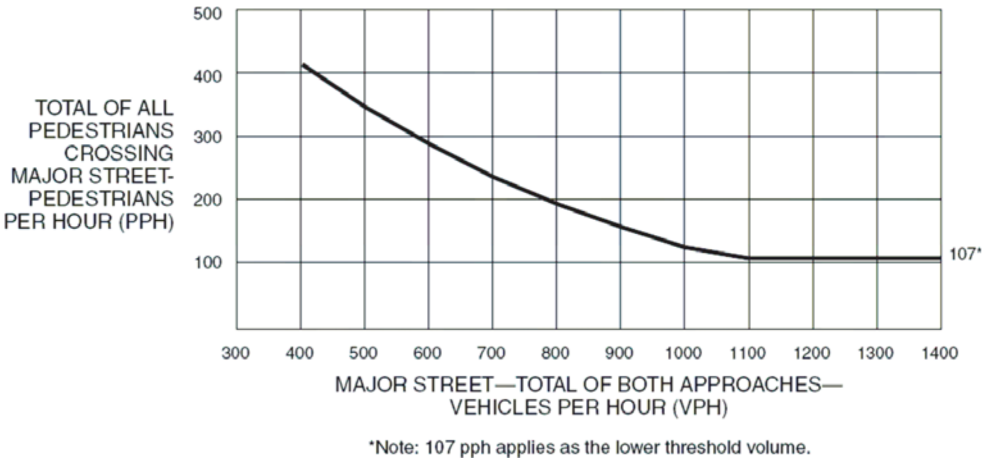


Figure 3. Warrant 4, pedestrian four-hour volume (source: FHWA 2009).

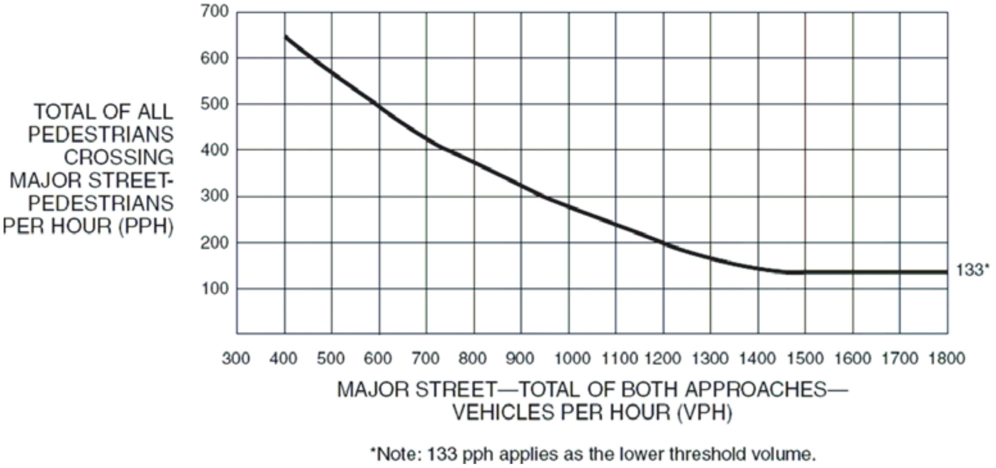


Figure 4. Warrant 4, pedestrian peak hour (source: FHWA 2009).

Last, traffic signals may be justified outside the bounds of the aforementioned MUTCD guidance if the 15th-percentile crossing speeds are less than the assumed 3.5 ft/s at all intersections. The MUTCD states that the pedestrian volume crossing the major street may be reduced as much as 50%.

In looking at international literature, a variety of pedestrian-related signal warrants from the United Kingdom, Canada, and Australia were identified. In Canada, the national MUTCD and an Ontario traffic manual provide pedestrian-based warrants for the installation of full traffic signals (City of Hamilton 2005). Intersection pedestrian signals, or half signals, are also used in some locations in Canada. Warrants and guidelines for these devices largely reside at the local level (or provincial level in the case of British Columbia) and include measures such as vehicular and pedestrian volumes, pedestrian delay, available gaps, roadway geometry, sight distance, speed, pedestrian demographics, and distance to the nearest adjacent signal.

In the United Kingdom, pedestrian traffic signals at roundabouts are fairly common. The warrant for such a signal is based on the formula $PV^2 > 10^8$, where P = pedestrian volume per hour (average of peak 4 hours) and V = vehicle volume per hour (average of peak 4 hours). Both sides of the splitter island must satisfy the criteria separately in order to meet the warrant (entry and exit volumes from roundabouts must be considered separately) (Baranowski 2004).

In Australia, some states have pedestrian-based warrants for full signals at intersections and midblock signals (Queensland 2003, New South Wales 2008). These warrants are similar to U.S. warrants in that they are primarily based on traffic and pedestrian volumes, with additional emphasis placed on available crash information. Additional wording is added to include warrants for signals that "cater mainly to persons with particular disabilities" including disabled, aged, or hearing-impaired pedestrians.

Specialized pedestrian signal applications such as the PHB [HAWK (high-intensity activated crosswalk)], Pelican, Puffin, and Toucan crossings (Fitzpatrick et al. 2006) have all been designed for midblock crossings. Installation of these devices at roundabouts presents a unique set of challenges. In many cases, such an installation would create conditions that are not recommended by the MUTCD.

- According to Section 4D.01 of the 2009 MUTCD, "Midblock crosswalks should not be signalized if they are located within 30 m (100 ft) from side streets or driveways that are controlled by stop signs or yield signs" (FHWA 2009). While not directly applicable to roundabouts, this suggests that proximity between a pedestrian signal and sign-controlled movement may cause confusion.
- According to Section 4D.13 of the 2009 MUTCD, signal heads should be located no closer than 40 ft and no farther than 180 ft from the stop bar, except where the width of an intersecting roadway or other conditions makes it physically impractical (FHWA 2009). The minimum distance is necessary to ensure that the signal head is visible through the windshield of a car. At a typical roundabout, the crosswalk is only 25 ft from the circulatory roadway. This would result in the stop bar being placed in the circulatory roadway to achieve proper signal head placement on the exit leg.
- Section 4D.12 recommends that "at signalized midblock crosswalks, at least one of the signal faces should be over the traveled way for each approach." In this case, mast arms would be needed for signalized crosswalks at roundabouts, which would increase cost.

In addition to the above sections, there is a general need to ensure that the signal indications on the roundabout entry do not create confusion with the yield sign at the circulating lane.

For any signal installation, the use of APSs is essential to ensure that the signal is accessible to pedestrians who are blind. APS installations commonly feature a push-button locator tone to help pedestrians find the pedestrian push button, and an audible signal or message that alerts the pedestrian when the walk phase is shown on the pedestrian signal display. Audible signals include variations of nonverbal sounds (cuckoo, chirp, or click) or a verbal message saying, for example, "Walk sign is on to cross [street name]." APS installations are a requirement for all new or altered pedestrian signal installations in the draft PROWAG by the U.S. Access Board (2005).

Although they are common in the United Kingdom and other countries, pedestrian crossing signals at roundabouts are rare in the United States. If signals are used at roundabouts, they are often installed as a two-stage crossing to reduce vehicle delays. In that case, a zigzag crossing geometry prevents the pedestrian from inadvertently crossing the entire roadway without sufficient crossing time. Currently, pedestrian signals of varying types have been installed in the United States at only a handful of roundabout intersections, including Salt Lake City, Utah; Charlotte, North Carolina; Clearwater Beach, Florida; Alpine City, Utah; and Oakland County, Michigan. Further information can be found in Appendix B.

Blind Pedestrian Crossing Experiments

In studies at roundabouts completed with support from a Bioengineering Research Program funded by the National Eye Institute (NIH 2010), researchers sought to document the street crossing behavior of people with total blindness at single- and multiple-lane roundabouts. In the initial study, conducted in 2000, adults who were totally blind and adults who were sighted made judgments at three Baltimore-area roundabouts about whether gaps in vehicular traffic were crossable, or were long enough to permit crossing to the splitter island before the arrival of the next vehicle without assuming any vehicular yielding. Trials were conducted at both exit-lane and entry-lane crosswalks of single-lane and two-lane roundabouts. Overall, blind participants were about 2.5 times less likely to make correct judgments than sighted participants, took significantly longer to detect crossable gaps, and were more likely to miss crossable gaps altogether. Further, the errors of blind participants were much more likely to be high risk than the errors of sighted participants at the two roundabouts that carried moderate and high volumes of traffic, in contrast to data collected at the lower volume roundabout. This research is reported in Guth et al. (2005). This research team also investigated judgments of gaps at a single-lane roundabout in Tampa, Florida, with large and predictable variations in traffic volume over the course of the day (Long et al. 2002). Blind participants made more high-risk judgments during peak hours than during off-peak hours. A similar pattern was not found for sighted participants. The judgments of the blind participants improved, although they remained risky, in a condition in which they made judgments at rush hour at simulated downstream crosswalk locations 60 ft from the actual crosswalks.

The work in Baltimore and Tampa involved making judgments about crossing without actually crossing. This left open the possibility that participants were using different judgment criteria than would have been the case had they actually crossed. To address this possibility as well as to follow up on several differences found in the earlier studies, the researchers conducted a third study in Nashville at a high-volume, two-lane roundabout. Blind and sighted participants made judgments without actually crossing during half of their trials and crossed during the other half. The Nashville findings validated the judgment-only measure, confirmed earlier findings, and provided important new data about pedestrian–driver interaction (Ashmead et al. 2005, Guth et al. 2005). A new measure used in the Nashville study was the frequency of interventions by an O&M instructor who followed the participants during crossing trials. Although interventions occurred in only a small percentage of trials (6%), the authors calculated a 99% probability of a serious pedestrian–vehicle conflict at this intersection if a person who was blind crossed daily for 3 months. A conflict was defined as a situation in which a crash is likely unless the driver or pedestrian takes immediate evasive action and is synonymous with events that resulted in an O&M intervention. Also, in post-experiment questionnaires, most participants who were blind reported that they would not cross at this intersection if they had any other option.

An alternative to crossing in a gap in vehicular traffic is to cross the street in front of a vehicle that has yielded upstream of the crosswalk. Geruschat and Hassan (2005) investigated the likelihood that drivers would yield to individuals holding a white cane and standing at a roundabout crosswalk, and contrasted these yielding data to data associated with individuals without white canes standing in the same location. This study, completed in Annapolis, MD, revealed that yielding rates overall were low, and varied as a function of vehicle speeds. Lower speeds were associated with higher yielding rates. The presence of the long cane resulted in only a modest increase in yielding rates. Also, when drivers yielded to a blind pedestrian, the pedestrian was often unable to detect the presence of the stopped (yielding) vehicle and would subsequently often fail to take the crossing opportunity provided. Yielding rates were higher at roundabout entry lanes than exit lanes. Inman, Davis, and Sauerburger (2005) reported that the mean observed time before vehicles yielded in both lanes was 63 s.

Inman, Davis, and Sauerburger (2005) reported the results of two studies related to the effectiveness of pavement treatments. Their first study, conducted on a closed course, was to evaluate the feasibility of a pavement treatment designed to alert blind pedestrians when vehicles have yielded to them. The second study examined drivers' yielding behavior at a two-lane roundabout, along with an evaluation of the effectiveness of the roadway treatment identical to that used on the closed course study. In the first study, there were two experimental conditions: a control condition and a treatment condition in which devices similar to rumble strips were placed on the roadway surface. Seven individuals with severe visual impairments participated. Participants stood at a crosswalk and used hand signals to indicate when they detected vehicles stopping or departing after a stop. Compared to the control condition, the sound-strips treatment increased the probability of detecting stopped vehicles and decreased by more than a second the amount of time needed to make a detection; however, the treatment did not reduce the number of false detections. The authors noted that false detections could result in the pedestrian crossing when moving vehicles are approaching the crosswalk. The second study was an experiment conducted at a double-lane roundabout. In that environment the rumble-strip-like treatment was not effective in increasing detection of yielded vehicles. The authors attributed this to the fact that the majority of vehicles stopped before crossing over the rumble strips. A "Yield to Pedestrians – State Law" sign that was placed in between the two travel lanes resulted in an increase in drivers' yielding from 11% of vehicles in the control condition to 16% in the experimental condition. It was concluded that the treatments explored in these studies do not appear promising for double-lane roundabouts but should be explored further to see if they might work at single-lane crossings.

The Long List of Pedestrian Crossing Treatments

Many different types of pedestrian treatments are available to aid engineers in designing safe crosswalks. Although there is limited guidance for choosing when a certain treatment should be implemented, there are resources that can assist in making good judgments. For instance, the Pedestrian Safety Guide and Countermeasure Selection System (Zegeer et al. 2002) is an Internet site dedicated to providing practitioners with up-to-date information on engineering, education, and enforcement to improve pedestrian safety and mobility. Another important source of information is *TCRP Report 112/NCHRP Report 562: Improving Pedestrian Safety at Unsignalized Crossings* (Fitzpatrick et al. 2006). This resource contains a detailed overview of pedestrian crossing treatments at unsignalized intersections and midblock locations and presents field study results on their effects on driver yielding behavior.

The treatment selection process for NCHRP Project 3-78A started with a long list of treatments that were believed to have potential in improving specific aspects of pedestrian accessibility. In the base condition, it is assumed that the sites meet current design and basic accessibility standards, including appropriate curb ramps, detectable warnings, and marked crosswalks. Under these baseline conditions, it is recognized that sighted pedestrians likely have better yield- and gap-detection capabilities and that delay and risk are higher for blind pedestrians. However, any treatment tested is hypothesized to also improve crossing conditions for sighted pedestrians, and for that matter any other special pedestrian populations, including children, wheelchair users, and the elderly. The research team identified 28 candidate treatments from various literature sources that showed initial potential to improve (blind) pedestrian accessibility by improving gap and yield utilization, minimizing risk, and reducing delay during the crossing task. In this research, treatments are grouped into six basic categories:

1. Driver information treatments,
2. Traffic calming treatments,
3. Pedestrian information treatments,
4. Crosswalk geometry modification,
5. Signalization treatments with APS, and
6. Grade-separated crossings.

Each category is intended to categorize treatments based on their principal intended effect on vehicle operations. They are discussed in more detail below, and Appendix B provides more detail as well as photographs of most of these treatments.

Driver Information Treatments

There is evidence (Fitzpatrick et al. 2006) that the use of static pedestrian crossing signs that are uncorrelated with actual pedestrian presence is unlikely to generate predictably high levels of driver yielding. This is not to say that all signing is ineffective or that signing is not required. However, several improvements over static roadside warning signs are possible and are summarized below.

- **Continuous flasher:** A continuous flashing beacon can be added to any static sign to make it more visible. The continuous flasher is a static device in that it will continue to flash whether a pedestrian is actually at the crosswalk or not. This type of treatment can become ineffective, especially if the available pedestrian traffic is not sufficient to provide feedback to the traveling public that the crosswalk is actually used on a frequent basis.
- **In-roadway warning sign:** In-street "Yield to Pedestrians" signs are placed in the roadway between travel lanes to increase the visibility of the crosswalk. The signs typically post messages such as "State Law – Yield to Pedestrians."

The signs give a third dimension to the usual crosswalk striping. Speed reductions associated with slight increases in driver compliance are expected with this type of treatment.

- **Active-when-present flasher:** This treatment looks similar to the continuous flasher; however, it is operated dynamically by activation of a pedestrian push button or by passive pedestrian detection. The dynamic push button activated beacon serves to increase the conspicuity of the static pedestrian sign. The treatment typically takes the form of a flashing beacon at the roadside, mounted overhead, or imbedded in the pavement.

Traffic Calming Treatments

Traffic calming is a method of designing streets using visual or physical cues to encourage drivers to reduce speeds. Traffic calming is largely self-enforcing in that the design of the roadway should result in the desired outcome of speed reduction. Traffic calming can be a very effective tool for reducing the severity and frequency of crashes and even noise levels. In addition, studies suggest that drivers are more likely to yield to pedestrians when traveling at slower speeds (Geruschat and Hassan 2005). Two possible treatment alternatives aimed at reducing vehicle speeds are described below.

- **Posting lower speed (15 and 25 mph):** This treatment considers posting regulatory reduced speed limit signs at 15 mph or 25 mph. This treatment represents the lowest-cost traffic calming treatment; however, the desired outcome is highly dependent on compliance of the driver. If the design of the roundabout does not encourage slower speeds (i.e., the deflection is not properly designed), then expected compliance of the posted lower speed is small unless heavily enforced. A lower regulatory speed limit for a CTL is impractical since it would also apply to the main line.
- **Raised crosswalk:** A raised crosswalk will reduce vehicle speeds as a function of its height relative to pavement surface and the transitional slope. A low and a gently sloping raised crosswalk would likely have higher speeds since vehicles easily maneuver over the crosswalk. Likewise, a steep incline to a high raised crosswalk could result in significant speed reductions; however, the reduced lane capacity may outweigh the benefit of the reduction in speed. Raised crosswalks also introduce vertical obstructions for ambulances and snow plows that need to be considered.

Pedestrian Information Treatments

This category includes treatments that provide pedestrians with audible information that can be used to make more informed decisions about when to safely cross using available yields and/or gaps. It should be noted that some treatments in this functional category have not been fully developed at this time but were still considered as a possibility as the team developed the research plan. The four possible treatment categories are:

- **Surface alterations/rumble strips:** Roadway surface alterations, such as rumble strips, generate auditory cues of approaching and/or yielding vehicles (Inman, Davis, and Sauerburger 2005). The treatment can also have the added benefit of providing information on the availability of crossable gaps. As an added benefit, the driver may be more cautious when approaching the crosswalk due to the additional sound cue provided by the treatment.
- **Yield-detection system:** The use of in-road sensors or video image processing to detect whether vehicles have yielded (stopped or slowly rolling) has shown promise in initial tests completed under a related NIH grant (NIH 2010). An auditory signal provides a speech message to the pedestrian indicating when a vehicle has yielded. The functional problems of such a system are primarily based on reliability of detecting vehicles that roll very slowly, queued vehicles stopped over the crosswalk (at the entry for instance), and in the event of a yielded vehicle that begins moving again.
- **Gap-detection system:** It is possible to use in-road sensors or video image processing to detect if there is an approaching vehicle (or no vehicle) within some predetermined safe crossing time or distance from the crosswalk. As with yield detection, the use of an auditory signal via an audible device is imperative to provide a speech message to the pedestrian indicating when it is safe to cross. The ability to sufficiently or accurately detect such gaps at roundabouts (especially the exit approach) and CTLs is not known at this time but is under development (NIH 2010).
- **Yield- and gap-detection system:** This treatment would combine the two previous treatments to take advantage of the yield- and gap-detection capability that could ultimately be possible. It is not known at this time whether such a system is even plausible since there has been no development of gap detection for pedestrian crossing treatments completed at this time.

Crosswalk Geometric Modification

There is the possibility of a modified crosswalk location or an alternative crossing location at roundabouts. This approach would place all or parts of the crosswalk further away from the circulating lane to separate pedestrian–vehicle interaction from vehicle–vehicle interaction at the roundabout. Supplemental treatments such as static signing, pedestrian-activated signs, and traffic calming techniques can all be applied in the distal crosswalk situation to further enhance accessibility.

Four variations of the concept of a relocated crosswalk are presented:

- **Distal crosswalk:** This treatment would relocate the crosswalk to a distance of approximately 100 ft from the circulating lane of the roundabout. The (presumed) benefit is the lower level of ambient noise at the crosswalk that is associated with moving the crosswalk further from the circulatory roadway. Driver benefits include reduced queue spillback issues in the roundabout with added storage capacity for the exit lane(s). Drawbacks of this treatment include potentially longer pedestrian walking distances, depending on the origin–destination patterns at the site. An additional drawback is that sighted pedestrians may ignore the distal crosswalk and cross closer to the roundabout unless physically restricted from doing so.
- **Traffic calming at distal location:** The distal crosswalk can be combined with other treatments to provide some traffic calming measures to reduce speeds, increase the likelihood of drivers yielding, and reduce the risk of collisions. Potential treatments include lowering regulatory speeds and the installation of a raised crosswalk.
- **Median island at distal location:** The distal crossing location would no longer have the benefit of a pedestrian refuge island since the roadway at that point is most likely undivided. Therefore, a distal crossing would require a one-stage crossing of both directions of vehicular traffic. A median island would provide pedestrian refuge and re-establish a two-stage crossing.
- **Offset exit crossing:** The potential effectiveness of this treatment rests on the premise that pedestrians (in particular, blind pedestrians) experience more difficulty crossing exit lanes than entry lanes. By offsetting the exit-lane portion of the crosswalk and creating a zigzag crossing, gap selection ability may be facilitated if ambient noise levels are in fact reduced relative to the typical crosswalk location. The zigzag configuration would further maintain and even enforce a two-stage crossing strategy and would provide supplemental queue storage at the exit lane.

The crosswalk modification treatments primarily apply to roundabout crossings. Some special considerations for geometric design at CTLs include:

- **Add deceleration lanes:** The use of deceleration lanes for traffic using the CTL has several potential advantages: (1) if vehicles, in fact, slow down in the deceleration lane, slower vehicle speeds can increase the likelihood of drivers yielding to pedestrians, and (2) when used in conjunction with some type of audible surface treatment, such a cue may facilitate crossing decision-making.
- **Remove acceleration lanes:** While facilitating the movement of traffic exiting the CTL, acceleration lanes are often associated with higher vehicle speeds. Higher vehicle speeds are associated with a decreased likelihood of drivers yielding and an increased injury rate in the event of a collision.

Signalization Treatments with APS

Signals at roundabouts and channelized turn lanes represent a more costly and intrusive treatment for providing a safe crossing environment for pedestrians. Traffic signals may introduce delays to both pedestrians and vehicles. Additionally, depending on signal timing and placements, vehicle queues can spill back on the roundabout exit from the signal to affect roundabout circulating flow or CTL through movements. However, APS-equipped signals can be effective at stopping traffic and at providing the pedestrian with visual and auditory cues of when the crossing phase is active. CTL signal impacts can be reduced through coordination with phasing at the main intersection and to avoid the likelihood of queue spillbacks onto the through lanes. Pedestrian signals with a walk indication can and should be outfitted with an APS to provide auditory cues in addition to the visual signal display.

- **Pedestrian scramble phase:** This signal strategy stops all vehicular traffic at the roundabout intersection to allow pedestrian movements in any and all directions (along marked crosswalks). Pedestrian activation at any approach of the facility would (following some minimum green time for vehicles) produce a red signal *at all entry lanes.* Following a clearance interval designed to allow all vehicles in the circulatory lane to exit the roundabout, a pedestrian walk signal would be presented to all pedestrians waiting to cross. This treatment alternative enables pedestrians to cross in a single stage. Following the pedestrian walk phase, vehicles at all entry lanes would be given a green signal to proceed. While simple in concept and in operation, the effectiveness of such a signalization strategy has yet to be determined. This strategy likely has little application to CTLs.
- **Pedestrian-actuated traditional signal – one or two stage:** This treatment uses a traditional traffic signal for pedestrians at (typically) unsignalized locations such as a roundabout or CTL. The signals are standard red-yellow-green traffic signal heads that rest in green when no push-button activations are in place. The treatment is particularly useful for blind pedestrians because the signal provides auditory information about phase indication via APS, much like they are accustomed to from a conventional intersection. In areas with high traffic and/or pedestrian volumes, delay and queue spillback at roundabouts could be problematic,

especially with false (unused) pedestrian actuations. Also, because the signals rest in green the majority of the time, it is possible that drivers may react slowly (or not at all) to the red stop indication.

- **Pedestrian hybrid beacon – one or two stage:** The PHB or HAWK signal aims to be more efficient than a conventional signal by allowing vehicular traffic to move during the pedestrian "Flashing Don't Walk" phase. During that phase a flashing red indication for drivers allows traffic to proceed after stopping if no pedestrian is in the crosswalk. This phasing scheme allows for less vehicular delay while providing similar pedestrian-related benefits to a regular signal.
- **Distal pedestrian-actuated signal – one or two stage:** Entry-lane and exit-lane pedestrian-activated signals used at a distal crosswalk location or in a zigzag configuration could be used to establish a one- or two-phased pedestrian crossing that maximizes the storage capacity of the exit lane during a vehicle red phase. If a two-phase crossing is used, a median refuge island would be necessary. Depending on pedestrian route patterns, these configurations may result in an increase in the travel time for pedestrians compared to a crossing at the traditional splitter island.
- **Distal/zigzag PHB – one or two stage:** The PHB could also be used at a distal location or in a zigzag arrangement, combining the advantage of the extra queue storage capacity at the exiting approach of the roundabout with more efficient signal phasing. Depending on pedestrian route patterns, these configurations may result in an increase in the travel time for pedestrians compared to a crossing at the traditional splitter island. The location of the distal crosswalk requires a median refuge island to be utilized if a two-stage crossing is necessary.

Grade-Separated Crossing

Grade separation allows pedestrians to cross the road without affecting the movement of vehicles. Grade-separated facilities must accommodate all persons, including those with vision and mobility impairments. To accommodate all users, these treatments may require ramps or elevators. Grade separation is typically used in cases where pedestrians must cross very busy streets or freeways, and where pedestrian volumes are extraordinarily high. Grade-separated facilities should not be considered where opportunities for crossing at the street level are available on a regular basis because this discourages use of the facility.

- **Pedestrian overpass:** Overpasses are the more common form of grade separation in the United States and are accessible via stairs, ramps, or elevators. Overpasses should be designed so that they provide the ability for multiple users to pass by or around each other.
- **Pedestrian underpass:** Pedestrian underpasses are most easily accounted for and installed during the design and construction process. Underpasses installed as a retrofit require costly underground construction. Underpasses may be difficult to keep clean and safe, but with proper design and lighting these challenges can be overcome.

CHAPTER 3

Methodology

This chapter describes the field data collection methodology used in this research. It discusses the experimental design and field methodology that were used to collect data with blind study volunteers at the test locations. It further discusses the process of identifying and selecting treatments, which ultimately led to the decision of which treatments should be tested in the field. The chapter then presents a summary of the site selection process and describes the treatment and sites used in the NCHRP Project 3-78A studies.

Experimental Design and Field Methodology

The general procedure used for crossing trials replicated field methodologies from previous work by research team members. To determine the effect of treatments, a pretest–posttest, within-participant design was used. In other words, participants were recruited to complete pretest crossings, and then returned for a second study (posttest) after one or more treatments were installed at the site. This experimental design allowed the team to control for confounding factors. By using the same participants for baseline and after-treatment data collection, each participant served as his or her own control, which provided more statistical power when using a relatively small number of participants. Therefore, all participants in the posttest had also participated in the pretest to allow for a direct within-participant comparison, although not all participants returned for the second round of testing. The same basic procedure was used in all studies for this project.

In each session, the participant made crossings back and forth on each experimental crosswalk, using a white cane and determining when to begin crossing independently. Participants were assisted with aligning to cross or maintaining alignment during crossings, as needed. Only one individual participated at a time, completing a number of crossings in each session. As in previous studies, participants were allowed to cross at their own pace and using their own judgment of when to begin crossing. Participants were accompanied at all times by a certified O&M specialist. If a participant decided to begin crossing at a time that the specialist judged to be unsafe based on vehicle positions and speeds, the O&M specialist stopped the participant, usually by grasping the participant's arm or shoulder. This is referred to as an *O&M intervention* and is later used as a safety performance measure in the analysis. The same O&M specialist was used in all experimental trials performed in this research to ensure uniformity of instructions and consistency in behavior, particularly as related to O&M interventions.

After all participants had completed the pretest, treatments were installed. The posttest was conducted after a driver adaptation or acclimation period, which allowed drivers to become familiar with the treatments. The posttest procedure was identical to the pretest procedure, except for changes related to the treatments (for example, pushing the push button on the pedestrian hybrid beacon).

Participants

Participants were individuals who were blind with light-perception or less vision and who had no ability to visually detect crosswalk lines, poles, objects, or vehicles. Participants were individuals who traveled independently using a long cane or guide dog and reported that they typically crossed streets independently. This was done in an attempt to draw a sample of participants from an appropriate target population of blind pedestrians who might cross at the experimental locations outside of the studies. A local O&M specialist in each city assisted in recruitment of participants based on these criteria. Participants who were guide dog users were also proficient in long cane use. All participants used a long cane during the crossings because repetitious street crossings are confusing for guide dogs. Participants were identified by recruitment coordinators and screened via a phone interview to determine if they met the criteria for the research. Written consent was obtained before any data was collected, using consent materials approved by the IRB at Western Michigan University and NAS (Appendix N). The participants received an honorarium and were provided transportation assistance as needed. Participation was strictly voluntary, and participants were allowed to withdraw from the experiment at any time or for any reason. The honorarium and transportation assistance were provided independent of whether a participant completed all trials. Sixteen to 18 participants were recruited for the pretest in each location, with approximately 12 individuals completing both pretest and posttest at each site.

Orientation

After consent was obtained, participants were oriented to the roundabout or CTL by the O&M specialist. Orientation included using tactile maps; walking around the facility with the experimenter, who described features; walking across the crosswalk while guided by an experimenter; and then crossing independently using the experimental procedure. Participants were encouraged to ask questions about the layout of the intersection and crosswalks, the traffic movement, the pedestrian facilities available, and any other features of interest. During the posttest, orientation included a description and demonstration of the treatments and their operation.

Procedure

Participants were instructed to cross whenever they believed it was appropriate to do so, using the cues that were available (traffic in pretest, and combination of traffic and treatment-related cues in posttest). Participants crossed a specified number of times at each site. The number of crossings was determined through pilot testing at each location to fit within the approximately 90 min experimental timeframe and to not result in inordinate fatigue for participants. Each participant made six round trips (entry, exit, exit, entry or exit, entry, entry, exit), or 24 crossings, at the Charlotte, NC, single-lane roundabout; 20 round trips or 40 crossings at the CTLs; and 12 round trips, or 48 crossings, at the Golden, CO, sites (four round trips at the single-lane roundabout and four round trips each at both the two-lane roundabout crosswalks). These sites are described further later in this chapter. A trial was defined as a crossing of one approach, which could entail one or two lanes of traffic depending on the site (e.g., single-lane or two-lane roundabout). Trials were blocked by crosswalk (for sites with multiple test approaches) to save time and to avoid confusing the participants. The starting location (e.g., entry or exit leg at a roundabout) was systematically varied to control for order effects. Posttesting was conducted at the same crosswalks as pretesting.

For each trial, participants were guided to the middle of the curb ramp and were aligned to face across the crosswalk. While approaching the crossing location, participants were told which lane of the roundabout they were crossing, which direction traffic would approach from, and whether they were crossing from the island or curb. For example: “You are crossing the entry lane of Davidson from the curb, with traffic coming from your left [touch left shoulder]. Cross whenever you’re ready.” Participants were reminded that the experimenter merely informed them when the trial began, not that it was a safe time to begin crossing. Before beginning trials, they were told that after the experimenter said “cross whenever you’re ready,” they should identify a safe time to begin crossing and then cross the street. The experimenter stopped each participant on the opposite side of the street (or on the island) at the end of that trial. After at least one vehicle had crossed the crosswalk (or 30 s, approximately, if no vehicles), the experimenter guided the participant to the starting point for the next crossing and began another trial.

Participants were allowed to take breaks as needed, and refreshments were provided. After all crossings were completed, each participant completed a short debriefing questionnaire.

Participant Questionnaires

After each testing session, each participant completed a debriefing questionnaire. The questionnaire was intended to ask the participant about the crossings just completed and to learn about their confidence in crossing at that location. Questions included, for example:

- “How would you rate your confidence in your ability to cross here safely on a scale of 1 to 5, with 1 being not at all and 5 very confident?”
- “Would you use this crossing if it was on the most direct route to and from work?”

Other debriefing questions focused on crossing strategies, the perceived difference between entry and exit lanes at roundabouts, the difference of crossing from the curb or the splitter island, and information about the treatments. Questions included, for example:

- “What cues did you use to decide when to cross?”
- “Did it matter whether you were crossing to or from the island?”
- “Were you using the sound from the strips to help you decide?”
- “Did you think the flashing yellow beacon made a difference in driver behavior?”

While the responses to these survey questions are subjective, they add an important feature to the analysis. The results are presented in Chapter 5 along with more objective performance assessment, such as the average delay time. Appendix G shows the questionnaires used during the debriefing process for different sites.

Identification and Selection of Treatments

This section describes the process used by the research team to collectively arrive at a set of treatments to be experimentally applied at selected single- and two-lane roundabouts and CTLs. The objective of the treatments was to improve access for blind pedestrians. The definition for what constitutes an accessible crossing and the performance evaluation framework used in the analysis is presented in Chapter 4. The treatment selection process combined information on treatment effectiveness available in the literature and the applied research and practical experience of those on the project team.

Given the operational similarities of roundabouts and CTLs discussed in Chapter 1, comparable treatment strategies were hypothesized to enhance accessibility at both facility types. Accessibility for blind pedestrians at these types of facilities is a function of (1) traffic conditions associated with a low occurrence of naturally occurring crossable gaps, (2) blind pedestrians' ability to detect the presence of naturally occurring gaps, (3) the likelihood of motorists yielding to pedestrians, and (4) the ability of blind pedestrians to reliably detect those yield events. Given the dynamic nature of the pedestrian–vehicle interaction, the temporal efficiency is another critical aspect since gap duration and driver patience (in yielding) are limited.

In addition to the above conditions for crossing, *equivalent* access to these types of facilities by blind and sighted pedestrians will also be a function of how effectively the blind pedestrian can (1) locate the crosswalk, (2) correctly align for crossing, and (3) maintain alignment while crossing. Failures of facilities to support these requirements can result in (a) an increase in the total pedestrian travel time associated with crossing, (b) exposure to risk by crossing at an inappropriate (i.e., unmarked) crossing location, or (c) both an increase in crossing time and exposure to risk associated with veering during the crossing. While the focus of the experimental trials in this research was on the actual crossing task, these other aspects are discussed in general terms.

The long list of treatments given in Chapter 2 represents all treatments that were deemed to have some potential in improving the accessibility of roundabouts and CTLs. It was beyond the scope of this project to test all of these treatments at multiple facility types. Consequently, a process had to be devised to arrive at a short list of treatments to propose for further testing. Having completed the literature review on treatment types and effectiveness and having extensive prior research and field knowledge in the engineering and accessibility fields, the research team represented a diverse and qualified group for this task. Therefore, an independent internal team survey was conducted to weigh different treatment options in terms of their perceived effectiveness, cost, and applicability to the different facility types.

Internal Team Survey

The internal team survey was intended to reduce the long list of treatments to a short list to move forward in the field-testing stage of the project. A survey tool was developed to gather the input of all members of the research team. The survey tool and team results are provided as Appendix C.

Each member of the research team evaluated each of the potential treatments in terms of (1) the extent to which each of the treatments would have an impact on the likelihood of gap detection (estimated separately for blind and sighted pedestrians), (2) the likelihood of having an impact on yield detection, and (3) the likelihood of drivers yielding to pedestrians. These are referred to in the survey as *behavioral attributes* associated with treatments. Estimates were also provided for the extent to which each potential treatment was believed to have an impact on performance (i.e., both the delay and risk experienced by blind and sighted pedestrians), as well the effect on vehicular traffic. Estimates were also provided for the perceived applicability of treatments for implementation at single- and two-lane roundabouts and at CTLs.

Treatments were divided into six categories following the discussion in Chapter 2: driver information treatments, traffic calming treatments, pedestrian information treatments, crosswalk geometry modification, signalization with APS, and grade separation.

The survey results suggested that most driver information treatments and traffic calming treatments were judged to have no substantial impact on blind pedestrians' ability to detect gaps and/or yielding vehicles. However, these treatments were generally believed to be beneficial to sighted pedestrians and were believed to be applicable to single-lane roundabout and CTL crossings, but to a lesser extent to two-lane roundabouts. While they weren't believed to affect detection of crossing opportunities, their perceived impact on increasing frequency of crossing opportunities (more yields) was deemed beneficial. At a relatively low cost and perceived low impact to vehicular operations, one treatment in each of these categories was considered for further testing: a pedestrian-actuated flashing beacon and a raised crosswalk.

For pedestrian information treatments, members of the research team hypothesized mixed effects on gap and yield detection, although generally higher effectiveness than treatments in the previous category. Estimated effectiveness for blind pedestrians was moderate for surface treatments intended to generate additional acoustic cues and higher for more automated methods of gap and yield detection. It should be noted that, although considered in the internal survey, automated gap and yield detection capabilities of the type that have undergone preliminary field evaluation in the NIH/NEI project (NIH 2010) are beyond the scope of what are considered off-the-shelf treatments available for evaluation by NCHRP Project 3-78A. Such treatments, while promising, are too experimental at this point to be considered as available treatment options for state DOTs. The concept of a surface sound-strip treatment showed potential in prior research (Inman et al. 2005) and was considered for further study at single-lane roundabouts and CTL crosswalks.

Signalization treatment options generally showed moderate to high potential for reducing delay and risk for blind pedestrians. As might have been expected, vehicle delay was judged to be negatively affected for signalized treatments. Of special interest was the PHB, an innovative signalization strategy that reduces vehicle delay through unconventional phasing while still providing a red vehicle display and associated walk phase for pedestrians.

Initial estimates of potential treatment effectiveness were also obtained for crosswalk geometry modifications and showed moderate potential in the ability of blind pedestrians to detect gaps and yields. Lastly, grade-separation treatments were rated as having the highest potential impact on behavioral parameters and performance measures. However, the applicability of modified crosswalk geometry and grade separations as treatment options to be considered under this research effort was low due to the high costs and permanent nature associated with the treatments.

Treatments Recommended for Installation

The results of the team treatment survey were used to develop recommended treatments or combinations of treatments for installation at the test locations under consideration of the project scope and budget. Each installation required cooperation from a municipality, was associated with installation cost, and required substantial team resources for data-collection planning, execution, and analysis. Treatment recommendations were chosen based on the perceived level of effectiveness in producing a measurable impact on the occurrence of yielding events or utilized gaps. Recommendations also considered the level of cost associated with installing the treatment and the expected benefit to travelers. Due to the relatively low number of available sites willing to install treatments, as well as budget constraints that limited the number of sites for which data could be collected, combinations of treatments were considered a plus. Based on these factors, the team recommended installing two treatment installations. The team recommended testing these treatment combinations concurrently at two CTLs of the same intersection in order to make most efficient use of project resources and to allow for a direct comparison using the same participants.

- **Channelized turn lane:** The team recommended installation of sound strips and lane delineators to provide additional auditory information to blind pedestrians about traffic patterns in the CTL and to distinguish that traffic from adjacent through movements. The team further recommended testing the sound strip and lane delineator treatment in isolation and supplemented with a pedestrian-actuated flashing beacon. The latter was intended to test the effect of enhancing pedestrian visibility to the driver and the effect of the treatment on increased yielding behavior. This proposed approach provides a measurable effect of three possible CTL treatments: the effect of sound strips, the effect of sound strips in combination with a pedestrian-actuated flashing beacon, and the flashing beacon alone (derived from the net difference between the two installations). The use of lane delineators was a fixed addition, assuming that they would be necessary to ensure proper functionality of the sound strips.
- **Single-lane roundabout:** The team recommended the same treatments used for the CTL, but for obvious reasons without the lane delineators. Proposed treatments were sound strips in isolation and sound strips supplemented with a pedestrian-actuated flashing beacon. The same assumptions and control factors applied since two different approaches of the roundabout were recommended with similar geometries and traffic volumes.
- **Two-lane roundabout:** The team recommended installing two different treatments at two approaches of the same two-lane roundabout: A raised crosswalk (RCW) intended to slow traffic and increase yielding, and a PHB intended to stop traffic at a red signal display and to provide additional audible information to the blind pedestrian. The team concluded that installing these two significant treatments was reasonable given the perceived challenges at two-lane crossings and the draft PROWAG language.

Additional details on the specific treatment installations are provided after the discussion of site selection and along with the overview of the test sites.

Site Selection

The research team evaluated a list of potential study sites and selected those that were deemed suitable for further field investigation of the proposed treatments. Criteria for site selection included:

- Feasibility of implementing one or more of the desired treatments at a given site within project schedule and budget;

- Level of federal, state, and local support and cost sharing in implementing the proposed treatments;
- Sufficient vehicle and pedestrian demand to enable a meaningful evaluation of the treatment's impact on the system performance;
- Availability of adequate numbers of potential research participants who are blind and are in reasonable proximity to the sites identified for data collection tasks;
- Proximity of the sites to the data collection team and to one another to maximize use of limited budget resources; and
- Adequate representation of the various geometric conditions to be considered.

Identification of Treatment Site Alternatives

The research team used three methods to identify candidate sites. First, a solicitation for sites was posted on e-mail list serves. Appendix D contains aerial and site photographs of the sites identified in the responses to the request. In the second method of site identification, agencies and practicing engineers active in the planning, design, and construction of roundabouts were contacted. While roundabouts were not the only focus of the study, it was hypothesized that CTL sites would be readily identified in proximity to (more rare) roundabout sites. Agencies and companies contacted included Maryland State Highway Administration; Kansas DOT; Washington State DOT; New York State DOT; North Carolina DOT; California DOT; Florida DOT; City of Clearwater, FL; City of Kennewick, WA; City of Modesto, CA; City of Bend, OR; City of Portland, OR; City of Tucson, AZ; City of Golden, CO; Town of Vail, CO; MTJ Engineering; Roundabouts, USA; Ourston Roundabout Engineering; and Alternate Street Design. The team had follow-up meetings and/or telephone conversations with the Maryland State Highway Administration, Washington State Department of Transportation, New York State Department of Transportation, and Ourston Roundabout Engineering. The third method for site selection consisted of reviewing sites studied under NCHRP Project 3-72, "Lane Widths, Channelized Right Turns, and Right-Turn Deceleration Lanes in Urban and Suburban Areas" and *NCHRP Report 572: Roundabouts in the United States.*

Selection of Treatment Sites

Channelized Turn Lanes

Providence Road at Pineville-Matthews Road – Charlotte, NC. The selection of a channelized turn lane facility was tied to the location of roundabout sites since CTL locations are common to most jurisdictions. The research team considered four candidate sites, two of which were located in Charlotte, NC, and the other two in Towson, MD. Given that no sites were chosen for roundabout treatments in Towson, the decision was made to focus on turn-lane treatments in the Charlotte region. Ultimately, the intersection of Providence Road at Pineville-Matthews Road was selected for treatment evaluation.

The main intersection is signal controlled with an eight-phase actuated-coordinated signalization scheme and protected dual-left turns on all four approaches. The through movements on Providence Road and Pineville-Matthews Road have two and three lanes per direction, respectively. The site has CTLs on all four approaches, each yield controlled at the downstream merge and with deceleration lanes present. No acceleration lanes were present on any of the approaches. The posted speed limit on all approaches is 45 mph. Traffic volumes were high during the peak hour periods. Land uses near the intersection include office buildings, retail strip malls, and residential. Two of the four CTLs were selected for this study. Both served the right-turn movements from Providence Road onto Pineville-Matthews Road. Figure 5 shows the locations of the studied crosswalks at the southeast and northwest corner of the intersection.

Traffic volumes (in 2005) at the tested crosswalk in the southeast corner show 24-hour turning flows of 3,200 vehicles per day (vpd) and adjacent through traffic of 12,000 vpd. The downstream conflicting movement is composed of the opposing through traffic (10,600 vpd) and the opposing left turn traffic (3,000 vpd). Volumes at the northwest corner crosswalk are generally higher at 6,000 vpd in the CTL, and adjacent through traffic of 18,400 vpd. The downstream conflicting through flow was 22,400 vpd, and the opposing left turn was 2,700 vpd. Low pedestrian activity was observed at the site,

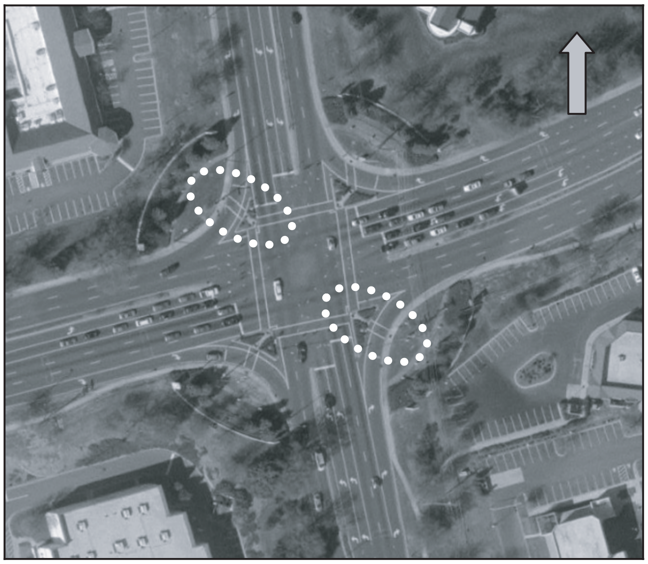


Photo by Google

This figure shows an aerial photograph of the CTL treatment site at the intersection of Providence Road and Pineville-Matthews Road in Charlotte, NC. The studied crosswalks are highlighted and located in the southeast and northwest corners of the intersection.

Figure 5. Aerial view of CTL site.

on the order of 20 pedestrians per day, primarily during the midday off-peak period. However, all main approaches of the intersection had marked crosswalks and pedestrian signals. Drivers were therefore believed to expect (occasional) pedestrian activity. In the pretest, crosswalks at the CTLs were unsignalized and outfitted with standard marking and pedestrian signage.

Figure 6 shows street-level photographs of each of the studied approaches and the installed treatment. The treatments were sound strips that were intended to increase the awareness of pedestrians of approaching vehicles at the northwest corner (SS-ONLY) and sound strips in combination with a pedestrian-actuated flashing beacon that was intended to increase driver yielding behavior at the southeast corner (SS+FB). Both approaches further had lane delineators installed to prevent late merges into the turn lane. This was necessary to ensure that the sound strips in fact picked up all right-turning vehicles.

The sound-strip treatment tested was an off-the-shelf, temporary, and self-adhesive rumble-strip material. The sound strips were white in color and had a vertical elevation of 0.25 in. The sound strips were evenly spaced over approximately 50 ft, and a total of 5 strips were installed at each turn lane. The first sound strip was installed at a distance of 10 ft upstream of the crosswalk. At a constant speed of 50 ft/s (34.1mph), this corresponds to a temporal spacing of the "clack" sounds of 1 s. A faster speed results in a shorter rate of clack sounds. A vehicle that slows down while traversing the sequence of sound strips will generate an audible pattern where the rate of clack sounds decreases as the vehicle slows (longer time between clacks). The sound strips therefore aim to accomplish two goals: (1) an audible distinction between right-turning (conflicting) and adjacent through traffic, and (2) an audible pattern that helps identify slowing or yielding vehicles.

The flashing beacons were installed on both sides of the street at the SS+FB corner and had a pole-mounted dual-head signal display. The beacons rested in "Dark" mode and flashed in wig-wag patterns (a 1-s flash frequency) for 20 s after a pedestrian pushed the button. The flashing beacon was further outfitted with a push-button integrated locator tone and an audible speech message, "cross with caution; cars may not stop," that was repeated concurrent with the flashing display.

Single-Lane Roundabouts

The research team considered four candidate sites: the Pullen-Stinson roundabout in Raleigh, NC, the two single-lane approaches to the Towson, MD, roundabout, a single-lane roundabout located in Voorheesville, NY, and a single-lane roundabout in Charlotte, NC. The Pullen-Stinson roundabout has been studied by research team members under other research grants. Based on the fact that other treatments have been used and evaluated at this site, the high proximity of the roundabout to the campus of North Carolina State University where pedestrian activity is extremely high, and the fact that other research trials as part of the NIH project were planned with blind participants during the project timeframe, the decision was made to eliminate this roundabout for study of further treatments. However, the analysis ended up including some prior data collected at the site. The Towson roundabout was intriguing; however, previous treatments installed at the roundabout were removed because of their negative effect on vehicular movements, which may be

Photo by Bastian Schroeder

Photo by Bastian Schroeder

This figure shows two photographs of the treatments installed at the CTL study site. The left photograph shows a view from the crosswalk splitter island down the deceleration lane with the sound-strip and lane-delineator treatments. The right photograph shows the view of a driver approaching the crosswalk with the sound strips, lane delineators, and flashing beacons installed.

Figure 6. Photo of sound strip and flashing beacon treatments.

problematic from the standpoint of installing new treatments for evaluation. The Voorheesville roundabout was considered problematic in terms of proximity to the research team.

Ninth Street at Davidson Street – Charlotte, NC. The site chosen for single-lane roundabout data collection was located at the intersection of 9th and Davidson streets in Charlotte. The urban roundabout site was close to the research team members, and the team was in contact with city personnel willing and able to install the necessary treatments. The site is located in a primarily residential neighborhood just northeast of uptown Charlotte, the city center. The inscribed diameter of the roundabout is approximately 140 ft (42.7 m), with approach speed limits of 25 mph (40 km/h). The crossing distance is approximately 16 ft (4.9 m) for each leg of the crossing. The major approach had average annual daily traffic (AADT) of 9,900 vpd, which is well within the capacity limits of a single-lane roundabout. Peak hour traffic counts showed total roundabout entering volumes of 830, 530, and 780 vehicles per hour (vph) for a.m., lunch, and p.m. peak periods, respectively. About 80% to 85% of these flows were on the major approaches on Davidson Street. Volumes on 9th Street were low at or below 100 vph. The team therefore concluded to focus the study on the two approaches along Davidson Street. Figure 7 shows the location of the two studied crosswalks, as well as a street level view of the southeast entry approach.

No posttest treatment evaluation was performed at this single-lane roundabout. The recommendation and direction not to proceed with treatment installation was made after the pretest was completed because it was decided that project resources were better spent elsewhere.

Pullen Road at Stinson Drive – Raleigh, NC. Although not officially part of the NCHRP Project 3-78A data collection effort, further analysis of an alternate single-lane roundabout was conducted to test the hypothesis that pedestrian crossing performance was affected by higher traffic volumes. The roundabout at the intersection of Pullen Road and Stinson Drive located in Raleigh was one studied previously by the research team. For this research, a supplemental evaluation was performed using pre-existing video of crossing trials prior to any treatment installation and using the same experimental protocol used in NCHRP Project 3-78A.

The roundabout is located in close proximity to the campus of North Carolina State University and has a high volume of pedestrian traffic from students walking to and from class. The roundabout has an inscribed diameter of 88 ft (26.8 m) and approach speeds of 25 mph (40 km/h). The crossing distance is approximately 13 ft (4.0 m). The AADT at this site is higher than at the Charlotte site at 15,000 vpd along the major approach, Pullen Road. Peak hour traffic counts showed total roundabout entering volumes on the order of 1,300 vph for a.m. and lunch peaks, and 1,500 vph in the p.m. peak. About 90% of these flows were on the major approaches on Pullen Road. Figure 8 shows the location of the studied crosswalk, as well as a view of the southern approach from an adjacent building rooftop. Since this site was originally studied under

Photo by Google

Photo by Bastian Schroeder

This figure shows two photographs of the studied single-lane roundabout at the intersection of Davidson Street and 9th Street in Charlotte, NC. The left image shows an aerial photograph with the studied crosswalks highlighted on the southwest and northeast approaches of Davidson Street. The right image shows a pedestrian-level photograph of the roundabout entry leg.

Figure 7. Aerial and pedestrian-level photographs of Davidson Street at 9th Street in Charlotte, NC – single-lane roundabout.

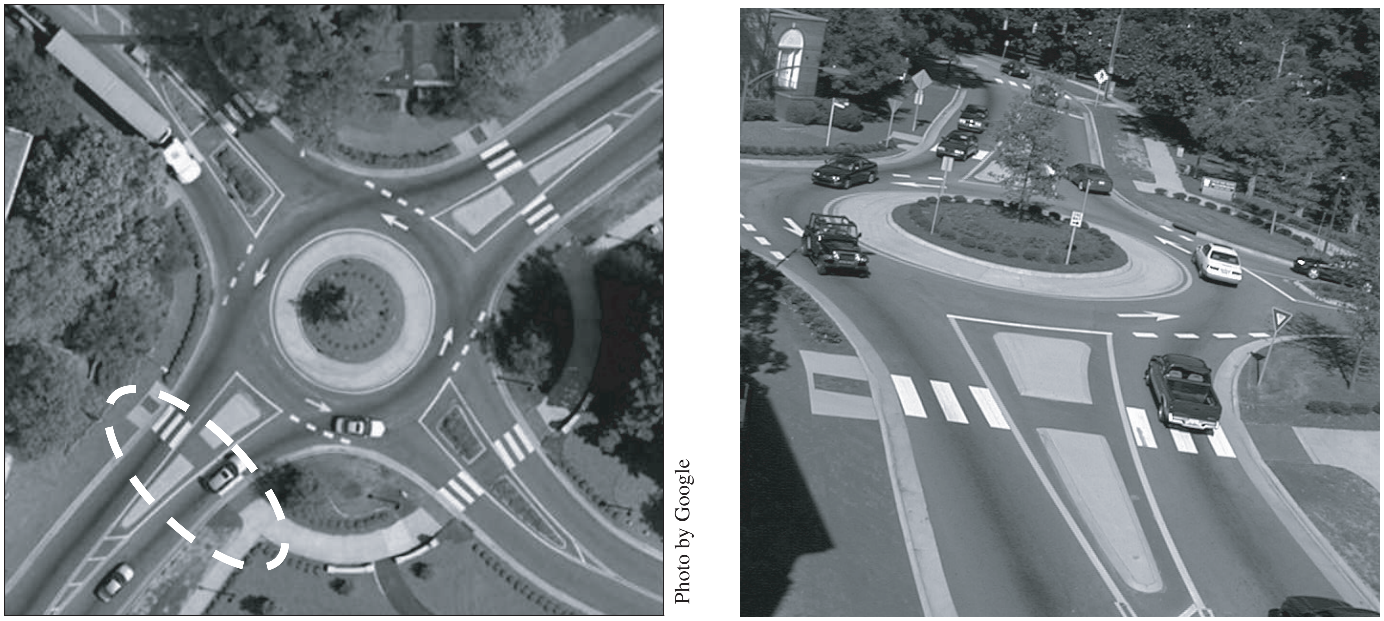


Photo by Google

Photo by Bastian Schroeder

This figure shows two photographs of the studied single-lane roundabout at the intersection of Pullen Road and Stinson Drive in Raleigh, NC. The left image shows an aerial photograph with the studied crosswalk highlighted on the southwest approach of Pullen Road. The right image shows a photograph of the studied crosswalk taken from a nearby building.

Figure 8. Aerial and pedestrian-level photographs of Pullen Road at Stinson Road in Raleigh, NC – single-lane roundabout.

a different research project, no NCHRP Project 3-78A treatments were installed.

Golden Road at Ulysses Drive – Golden, CO. One additional single-lane roundabout site was studied by the research team. This site, located in Golden, CO, was intended to provide a control condition for a nearby two-lane roundabout. The single-lane site was studied concurrently with the pretest and posttest treatment conditions at the two-lane site. Both roundabouts were on the same corridor (Golden Road). The purpose of this additional analysis was to test for a learning effect in the same participants returning to the same roundabout without treatment installation. It further allowed a direct within-participant comparison of the single-lane and two-lane roundabout crossing ability of the same participants.

The roundabout has a central island diameter of 100 ft (30.5 m), including a truck apron of 10 ft (3.1 m). The lanes at the studied crosswalk are 20 ft wide, partly to accommodate nearby roadside bus stops. The crosswalk is located approximately 60 ft (18.2 m) from the circulating lane measured at the exit side, and approximately 50 ft (15.2 m) from the roundabout yield line at the entry. The two-stage crossing is divided by a 6-ft, raised splitter island, but the crossing itself is at pavement elevation. No pedestrian-detectable warning surfaces were installed on the splitter island, so the study participants were instructed by the O&M specialist when they completed the first half of the crossing. No detectable warning surfaces were installed on the crosswalks at this roundabout. The crosswalk was marked and outfitted with standard pedestrian signage. Traffic volumes on Golden Road indicated an AADT of 15,000 vpd. Figure 9 shows the location of the studied crosswalk as well as a street view of the eastern approach.

Two-Lane Roundabout

The research team identified three candidate two-lane roundabout sites, in Gatineau, Quebec, Canada; Towson, MD; and Golden, CO. The Gatineau site already had a signal installed and would have therefore prevented the team from performing a pretest and posttest comparison. The Towson site has a very good mix of pedestrian and vehicular traffic, with heaviest pedestrian traffic during the middle of the day. This site also offers the advantage of providing a mix of single-lane and two-lane entries/exits. However, the geometry is very different from most single- or two-lane roundabouts, which was an important consideration in rejecting the site. Further, the local agency was only supportive of treatment installations short of signalization.

Golden Road at Johnson Road – Golden, CO. The two-lane roundabout site finally selected for installation of treatments was located in Golden. The site provided two good approaches for treatment installations, and the team enjoyed significant local support for the research effort and treatment installation. Figure 10 shows an aerial view of the site and the locations of the studied crosswalks. The PHB treatment was

Photo by Bastian Schroeder

This figure shows two photographs of the studied single-lane roundabout at the intersection of Golden Road and Ulysses Street in Golden, CO. The left image shows an aerial photograph with the studied crosswalks highlighted on the east approaches of Golden Road. The right image shows a pedestrian-level photograph of the roundabout entry leg.

Figure 9. Aerial and pedestrian-level photographs of Golden Road at Ulysses Street in Golden, CO – single-lane roundabout.

installed on the northwest corner, and the raised crosswalk was installed on the southeast corner.

The roundabout has a central island diameter of 90 ft (27.4 m), including a truck apron of 10 ft (3.1 m). The lanes at the studied crosswalk are 11 ft wide (3.4 m), resulting in a total crossing distance of 22 ft (6.8 m). The crosswalk is located approximately 30 ft (9.1 m) from the circulating lane at the northwest corner, and approximately 20 ft (6.1 m) at the southeast corner. The two-stage crossings are divided by 15-ft raised and landscaped splitter islands. Detectable warning surfaces were installed on the splitter islands and on the curbs at both crossings. The crosswalks were marked and outfitted with standard pedestrian signage. Traffic volumes on Golden Road indicated an AADT of 15,000 vpd. Peak hour total entering flows at the roundabout were 1,900 vph in the a.m. peak and 2,100 vph in the p.m. peak. Traffic volumes were highest on the two Golden Road approaches (approximately 70% to 75% of entering traffic).

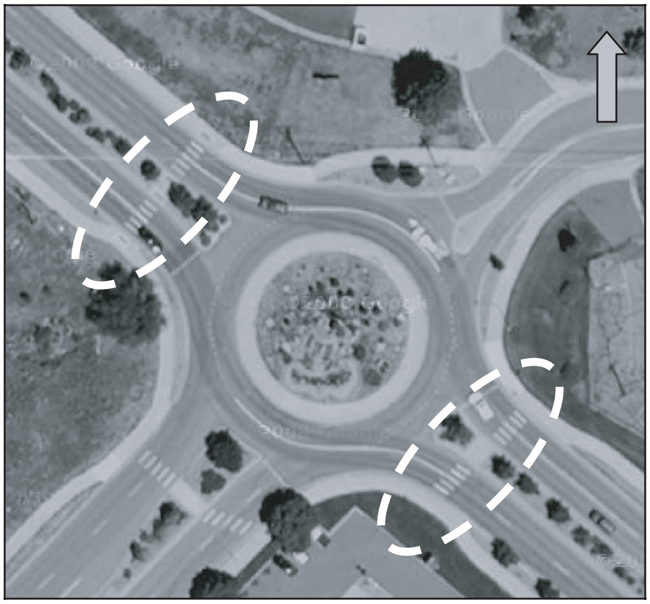


Photo by Google

This figure shows an aerial photograph of the two-lane roundabout treatment site at the intersection of Golden Road and Johnson Road in Golden, CO. The studied crosswalks are highlighted and located in the southeast and northwest approaches of Golden Road.

Figure 10. Aerial view of Golden Road at Johnson Road in Golden, CO – two-lane roundabout.

Figure 11 shows a photograph of the RCW installed at the southeast approach of the roundabout on Golden Road. The RCW was installed at a vertical elevation of 3 in. from pavement surface and a transitional slope of 1:15. This means that the transition to the 3-in. elevation occurred over approximately 45 in., or just short of 4 ft. This installation resulted

Photo by Janet Barlow

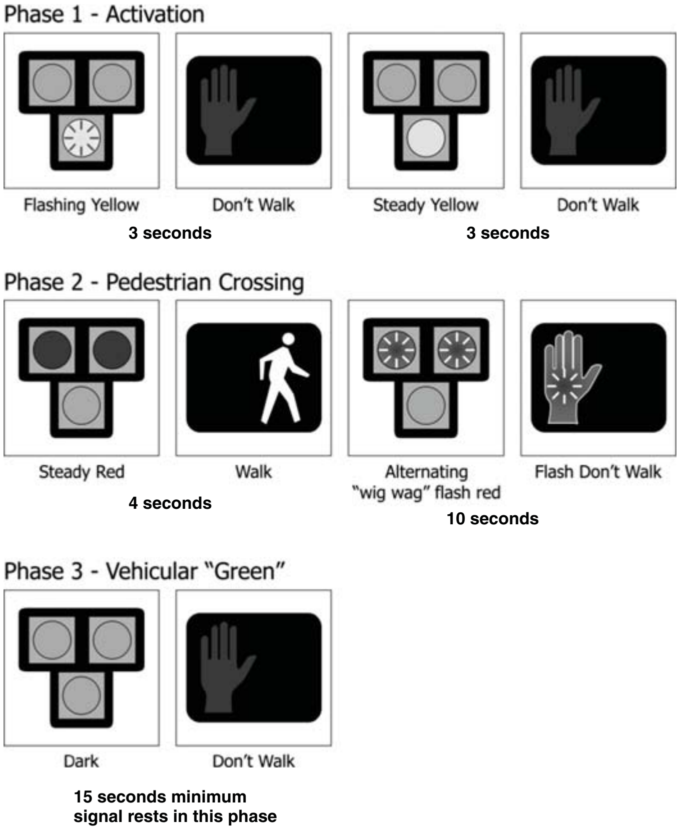
This figure shows a pedestrian-view photograph of the RCW treatment installed at the southeastern approach of the Golden Road two-lane roundabout.

Figure 11. Raised crosswalk treatment – Golden, CO.

Photo by Lee Rodegerts

This figure shows a pedestrian-view photograph of the PHB treatment installed at the northwestern approach of the Golden Road two-lane roundabout.

Figure 12. PHB treatment – Golden, CO.



This figure shows a graphic of the PHB phasing scheme. The sequence of vehicle/pedestrian displays is "Flashing Yellow/Don't Walk," "Steady Yellow/Don't Walk," "Steady Red/Walk," "Flashing Red/Flashing Don't Walk," and "Dark/Don't Walk." Phase durations for these phases in sequence are 3 s, 3 s, 4 s, 10 s, and 15 s, where the last represents a minimum time for the "Dark/Don't Walk" and the PHB rests in this phase if no further pedestrian calls are placed.

Figure 13. PHB phases and signal timing.

in a less severe impact on vehicle traffic compared to other installations visited by the research team. Other installations of RCWs commonly feature vertical elevations up to 5 in. and/or transitional slopes as steep as 1:10. Clearly, the speed reduction effect is greater with higher vertical elevation and a steeper slope.

The RCW was intended as a temporary installation. It was therefore simply installed on top of existing pavement and used the existing curb and gutter system for drainage. This resulted in the RCW being sloped downward on each side. A permanent installation would likely be installed flush with the sidewalk and incorporate drainage into the RCW design via piping. As a result of this installation, pedestrians first walked down the curb ramp from sidewalk level and then back up onto the crosswalk. Numerous participants noted that this unexpected down/up transition was uncomfortable to walk on. The RCW installation therefore satisfied the intended treatment effect (on traffic), but the pedestrian aspects of the design should be modified for a permanent installation. Pavement markings were as shown in Figure 11 and emphasized the upslope of the RCW.

Figure 12 shows a photograph of the PHB installation at the northwest approach of the roundabout on Golden Road. The PHB was installed on roadside poles following MUTCD requirements for vertical height and additional signage.

The PHB installation featured a total of four pole-mounted devices, with two each at the entry and exit legs. All four devices were outfitted with push-button integrated APS devices. The signal timing was such that the two sides (entry and exit) operated fully independently of each other. The vehicle display rested in "Dark" mode; the pedestrian display rested in "Don't Walk." The phasing sequence of the PHB after pedestrian activation and the times for each phase are shown in Figure 13.

After pedestrian push-button activation, the PHB entered a "Flashing Yellow" phase for vehicles (3 s), followed by a "Steady Yellow" phase (3 s). The pedestrian signal during both of these phases remained as "Don't Walk." Next, the vehicle display changed to a "Steady Red" phase, while the pedestrian displays showed "Walk" (4 s). The PHB then showed a "Flashing Red" for vehicles concurrent with the pedestrian "Flashing Don't Walk" (10 s). Finally, the vehicle display returned to "Dark" and the pedestrian display to "Don't Walk." The PHB was timed to rest in this phase for a minimum of 15 s before cycling back through the phases.

Expected pedestrian behavior at the PHB was as it would be at a standard pedestrian signal. Pedestrians were expected to push the button (since they observed a "Don't Walk" phase) and cross during the "Walk" interval. Drivers were expected to be stopped during the "Red" phase. The "Flashing Yellow" was intended to alert the driver of the impending signal phase change. The "Solid Red" offered drivers dilemma-zone protection in case they were too fast and too close to the crosswalk to come to a stop. Drivers were allowed to proceed with caution after having stopped during the "Flashing Red" phase, provided the pedestrian had cleared the crosswalk. This feature reduced the required stop time for drivers from 14 s to 4 s. Appendix F gives additional details on the PHB installation, including timing parameters and signal plans.

CHAPTER 4

Analysis Framework

This chapter presents the analysis framework used in NCHRP Project 3-78A. It discusses performance characteristics of pedestrians that are used to quantify the availability of crossing opportunities in the traffic stream, as well as the pedestrians' ability (or willingness) to successfully utilize these opportunities. This analysis framework was initially described in Schroeder and Rouphail (2007) and was later adopted in Schroeder et al. (2009), which are included in Appendices I and J, respectively. These characteristics are then tied to a set of accessibility criteria that were formulated in Schroeder et al. (2009). On the basis of these accessibility criteria, the chapter discusses analysis strategies for the collected field data, including definitions of pedestrian–vehicle events and variables used in the analysis. The results of the analysis are presented in Chapter 5.

Crossing Performance Characteristics

The analysis framework hypothesizes that the interaction of pedestrians and vehicles at unsignalized crosswalks can be described using principles of probability theory. Conceptually, pedestrians encounter two types of crossing opportunities: (1) gaps in between vehicles of sufficient duration to allow for a safe crossing, and (2) drivers yielding the right of way to pedestrians. The *likelihood of occurrence* of these events is described by the following probabilities:

- **P(CG):** the probability of encountering a crossable gap (CG) in the traffic stream and
- **P(Yield):** the probability of encountering a yield in the traffic stream.

The definitions for what constitutes a yield or a crossable gap are given later in this chapter. Given the complex auditory environment at roundabouts and CTLs and the lack of reliable cues to help identify these events, prior research (e.g., Guth et al. 2005, Ashmead et al. 2005, Schroeder et al. 2006) has established that pedestrians who are blind have difficulty discerning either of these events reliably. As a result, it is expected that the *rate of utilization* of gap and yield crossing opportunities is less than 100%, which is described mathematically by two additional probability terms:

- **P(GO|CG):** the probability of utilizing an encountered crossable gap and
- **P(GO|Y):** the probability of utilizing an encountered yield.

In the interpretation of these two probabilities, it is important to emphasize that it is often unclear from observational studies whether the crossing opportunities are *missed* (i.e., the pedestrian didn't hear the yielding vehicle) or *rejected voluntarily* (i.e., the pedestrian chose not to cross in front of the yielding vehicle). For observational studies, the objective description is that the opportunity was not *utilized*, which does not pass judgment about the reason for not crossing.

This approach for describing pedestrian crossing behavior is initially based on unsignalized crossings but can also be applied to signalized crossings. At a signalized crossing, pedestrians also encounter crossing opportunities in the form of gaps (no traffic) and yields (cars stopped at the signal), but with the caveat that these crossing opportunities tend to coincide with a particular phase in the signal cycle (i.e., the "Walk" phase). When applying this approach to a signalized crossing, the analyst should therefore make note of differences in these probability terms at different times in the cycle. Even at signals, some drivers may not yield (e.g., may run a red light) and (blind) pedestrians may miss crossing opportunities, especially when no audible signal is provided. The probability terms described above therefore provide a universal evaluation framework of pedestrian–vehicle interaction at crosswalks that can be applied independently of the presence of a signal.

Similarly, the above framework allows the analyst to quantify the impact of any other crossing treatments that are intended to facilitate pedestrian crossings but fall short of stopping traffic with a red signal indication. The framework therefore is sensitive to different treatment objectives, such as increasing the propensity of drivers to yield, P(Yield), or enhancing the ability of using crossing opportunities.

Crosswalk Usability Criteria

The crossing performance characteristics above provide a framework for quantifying pedestrian behavior from an observational study. For the purpose of establishing criteria for whether or not a crosswalk is accessible to and usable by a pedestrian who is blind, four accessibility criteria have been formulated. These criteria address different aspects of usability and together provide a comprehensive approach for quantifying crossing performance at a test location. The four crosswalk usability criteria, from Schroeder et al. 2009, are:

1. **Crossing opportunity criterion**
   - Are there *sufficient* crossing opportunities in the form of *yields* or *crossable* gaps?
2. **Opportunity utilization criterion**
   - Are the crossing opportunities *utilized* by the pedestrian?
3. **Delay criterion**
   - Is a crossing opportunity taken within a *reasonable time?*
4. **Safety criterion**
   - Do the crossing attempts involve a *significant degree of collision risk?*

Each of the four criteria is discussed in more detail below.

Crossing Opportunity Criterion

Crossing opportunities may take the form of yields or gaps. A yield is defined as a driver reducing the speed of the vehicle or coming to a full stop to allow a pedestrian to cross the street. Legislation in most U.S. states requires drivers to yield to pedestrians *in* the crosswalk, but the laws (and driver understanding of the law) vary in terms of the requirement to yield to pedestrians *at* the crosswalk. A nationwide survey of yielding practices at unsignalized crosswalks (Fitzpatrick et al. 2006) identified a wide range of yielding behaviors and further found varying levels of yield compliance for different pedestrian crossing treatments. Similar inconsistency was found for yielding behavior at roundabout crossings across the United States (Rodegerdts et al. 2007). For the purpose of this analysis framework, an increase in yielding directly affects the crossing opportunity criterion.

When crossing opportunities are presented in the form of gaps between successive vehicles, a threshold needs to be introduced to define what constitutes a *crossable* gap. The threshold for separating crossable and non-crossable gaps is proportional to the crossing distance (longer distance requires more time to cross) and inversely proportional to the pedestrian walking speed (slower walkers require more time to cross). It is further reasonable to implement some additional *buffer time* to account for some lost time before a crossing is initiated and some safety clearance time after the crossing is completed. The U.S. *Highway Capacity Manual* (HCM) (TRB 2000) defines the *critical gap* for pedestrians as the crossing distance divided by the walking speed, plus a safety buffer. This same concept has been applied in other research on pedestrian behavior (Yang et al. 2006; Rouphail, Hughes, and Chae 2005). For the purpose of this analysis framework, an increase in the occurrence of crossable gaps directly affects the crossing opportunity criterion.

The remaining critical definition in this criterion is the term *sufficient,* which describes whether there are enough crossing opportunities in the traffic stream. The determination of how many crossing opportunities are enough depends on the rate of utilization of opportunities (criterion 2) and ultimately on acceptable levels of delay and risk (criteria 3 and 4).

Opportunity Utilization Criterion

The second criterion quantifies the level of pedestrian utilization of the available crossing opportunities. The utilization of crossable gaps is a function of the gap acceptance characteristics of the pedestrian. It may further be influenced by background noise at the site. At roundabouts and channelized turn lanes in particular, the noise from background traffic may mask the auditory information at the crosswalk, affecting the ability of a blind pedestrian to identify a crossable gap or yield (Guth et al. 2005, Schroeder et al. 2006). Previous research has shown that pedestrians with vision impairments often do not cross in front of yielding vehicles because they either cannot hear the car or they are not confident that the crossing is safe despite the yield condition (Ashmead et al. 2005, Davis and Inman 2007). Multiple threat situations (FHWA 2004) at two-lane approaches, where a vehicle in the near lane visually and/or auditorily masks approaching vehicles in the far lane, further complicate yield utilization.

It has been demonstrated in ongoing research funded by the NIH (2010) that sighted pedestrians can successfully identify and utilize most (if not all) crossing opportunities they encounter. Clearly, individual differences remain, but with a relatively conservative definition of what constitutes a crossing opportunity (e.g., the crossable gap threshold), it is hypothesized that a yield and gap utilization rate of 100% represents a reasonable benchmark for what may constitute crossing behavior of a sighted pedestrian. While the first criterion is largely independent of the behavior (and any disability) of the pedestrian, this second criterion begins to distinguish between pedestrian groups with different travel skill levels. This distinction includes the difference between blind and sighted pedestrians (the focus of this research), but can similarly be applied to represent other special pedestrian populations such as children, wheelchair users, or the elderly.

Another caveat of the utilization measure is that it can be used to describe potentially risky behavior. For example, assuming that the defined threshold for a crossable gap is appropriate, any utilization of a non-crossable gap has the potential of increasing the rate of crossable gap utilization to something greater than 100%. This type of check also serves to validate that the crossable gap threshold was defined reasonably.

Delay Criterion

The first two criteria describe traffic conditions (gap availability), driver behavior (yielding rate), and pedestrian behavior (utilization). However, they ignore the temporal aspect of the pedestrian–vehicle interaction. Assuming that a pedestrian eventually utilizes a crossing opportunity, the third criterion describes how much delay was experienced prior to that crossing initiation. The *Highway Capacity Manual* (TRB 2000) uses delay to define levels of service for pedestrian crossings. From an engineering perspective, it is thus intuitive that an inordinate amount of delay would make a crossing inaccessible. In the HCM, a (sighted) pedestrian delay over 45 s at an unsignalized intersection corresponds to level of service (LOS) F, which is the worst category on an A through F scale. At a signalized crossing the corresponding LOS F threshold is 60 s, acknowledging that pedestrians may be more willing to accept higher delays if they have confidence that the signal will eventually provide them with an opportunity to cross. The HCM further emphasizes that the likelihood of risk-taking behavior (by sighted pedestrians) is *very high* at these levels of delay.

The usability of a crosswalk is improved with a reduction in criterion 3. It is expected that increasing levels in criteria 1 and 2 will result in an improvement (reduction) of pedestrian delay. Similarly, a low availability of crossing opportunities and/or a low utilization rate will increase delay. For pedestrians who are blind, experience with increasingly high delay at a particular crossing may lead people to avoid the crossing altogether, making it, in effect, inaccessible. Similarly, it can be argued that high delays (caused by low levels in criteria 1 and 2) may lead to an increased propensity to make risky decisions, as is hypothesized in the HCM. In this research, the study trials were capped at a time duration of 2 min.

Safety Criterion

The fourth criterion describes pedestrian safety at a crosswalk. Even if pedestrians encounter crossing opportunities and utilize them within an acceptable amount of time, the site remains inaccessible if these crossings occur in dangerous situations. Research (Schroeder et al. 2006) found that blind pedestrians make significantly more risky decisions than sighted pedestrians at unsignalized crosswalks at channelized right-turn lanes. A study of blind pedestrians crossing at a two-lane roundabout (Ashmead et al. 2005) found that the experimenter sometimes had to physically restrain the study participant from crossing to avoid a potential collision. The overall observed *intervention rate* was a clear indication of the risky nature of the studied two-lane roundabout crossing. The metric of intervention rates was also previously used at crossing studies at single-lane roundabouts (NIH 2010).

Field Evaluation Approach

The four crosswalk usability criteria were evaluated in controlled studies with blind volunteers as described in Chapter 3. The crossing trials were monitored by a field observer and were further videotaped for supplemental data extraction in the office. The analysis approach worked on the basis of *time-stamped events* that describe traffic conditions, driver behavior, and pedestrian behavior. The following section defines pedestrian–vehicle interaction events as used in this project, followed by a section of variable definitions and performance measures used in the analysis.

Event Definitions

The NCHRP Project 3-78A analysis used a performance evaluation framework that described the availability of crossing opportunities, the rate of utilization of these opportunities, and the delay and risk associated with the crossings. For a single-lane crossing, the yield and gap events are uniquely defined by the vehicle state in the conflict lane. However, at a two-lane crossing the analysis needs to consider the vehicle state in both lanes.

For a single conflicting lane, a pedestrian–vehicle event is defined as the interaction of one pedestrian and one vehicle. For each participant, the total number of events is therefore equivalent to the number of vehicles encountered during the crossing attempt(s). For a two-lane crossing, a pedestrian–vehicle event will be defined as the interaction of one pedestrian and one vehicle in the lane nearest to where the pedestrian is waiting. The vehicle state in the far lane is considered and will be discussed in more detail below.

For all types of crossings, a pedestrian–vehicle event has one of five outcomes:

1. **Rolling yield (RY):** Pedestrian encounters a driver who has slowed down for the pedestrian, but has not come to a full stop.
2. **Stopped yield (STY):** Pedestrian encounters a driver who has come to a stop, defined as moving at a speed less than approximately 3 mph.

3. **Forced yield (FY):** Pedestrians initiates crossing before the vehicle initiated the yield, forcing the driver to slow down by entering the crosswalk.
4. **Crossable gap (CG):** Pedestrian encounters a gap large enough to safely cross the street without the need for a driver yield. A crossable gap is defined as the time needed to cross at an assumed walking speed plus a safety buffer.
5. **Non-crossable gap (non-CG):** Pedestrian encounters a gap between vehicles shorter than the crossable gap threshold.

For event categories 1–3, the event is associated with the vehicle (driver) executing the yielding maneuver. For event categories 4 and 5, the event is associated with the second of the two vehicles that define the gap (the vehicle that "closes" the gap). Conceptually, event type 5 also represents a vehicle that did not yield to the pedestrian. The sum of event types 1 through 5 corresponds to the total number of vehicles encountered by the pedestrian. The five event categories are used to define the operational variables below.

Performance Measures

Using the five event outcomes defined above, the NCHRP Project 3-78A analysis framework defines performance measures to describe the four accessibility criteria: crossing opportunity, opportunity utilization, delay, and safety.

The first analysis component describes the availability and utilization of yields. Initially, all three yield types (rolling, stopped, and forced) are combined, but they can also be broken out for a more detailed assessment. Three performance measures related to yielding are defined, although only the latter two are used in the analysis:

- **P(Yield):** The probability of a driver yielding, defined as the number of yields divided by the total number of drivers that could have yielded.
- **P(Y_ENC):** The probability of encountering a yield event, defined as the number of yields divided by the *total of all pedestrian–vehicle events encountered* by the pedestrian until he/she completes the crossing.
- **P(GO|Y):** The probability of yield utilization, defined as the number of crossings in a yield divided by the total number of yields encountered by the pedestrian.

The P(Y_ENC) performance measure is different from the traditionally used probability of yielding, P(Yield), since it is calculated on the basis of all pedestrian–vehicle events and not just potential yielders. Figure 14 and the associated discussion provide an example that illustrates the distinction between the two measures.

The analysis next considers the availability and utilization of crossable gaps. For the purpose of this analysis, a crossable gap is defined as the time needed to cross the width of the crosswalk at a walking speed of 3.5 ft/s while allowing for a 2-s safety buffer. This 2-s buffer allows for some pedestrian reaction time before initiating the crossing as well as the safety buffer between a completed crossing and the next vehicle arrival.

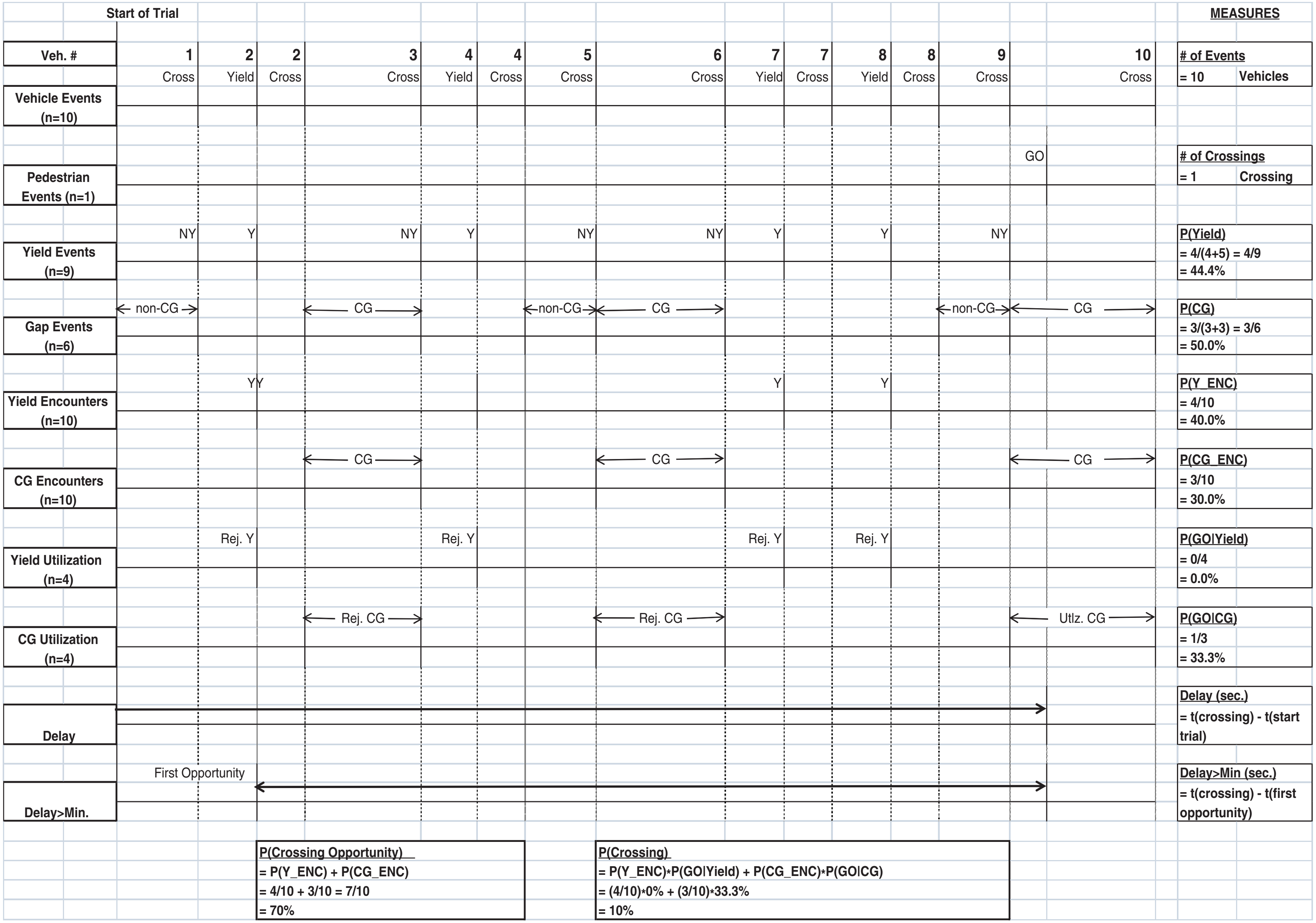
Similar to the yield statistics, three gap-related parameters are defined, but only the last two are used in the analysis:

- **P(CG):** The probability of a gap being crossable, defined as the number of crossable gaps divided by the number of crossable and non-crossable gaps encountered.
- **P(CG_ENC):** The probability of encountering a CG event, defined as the number of crossable gaps divided by the total of all pedestrian–vehicle events encountered by the pedestrian.
- **P(GO|CG):** The probability of crossable gap utilization, defined as the number of crossings in a CG divided by the total number of CGs encountered by the pedestrian. The gap utilization concept is related to other traffic engineering studies that evaluate the numbers of *accepted* and *rejected* gaps.

A walking speed of 3.5 ft/s in the determination of the crossable gap threshold is based on the proposed walking speed in the latest release of the MUTCD (FHWA 2009). This estimate represents the 15th percentile walking speed of the general pedestrian population, which is a conservative estimate. As a result, the crossable gap threshold used in this project is also conservative. It is expected that most sighted pedestrians would likely accept gaps that are shorter than this calculated threshold, and this may also be observed for some of the blind study participants. The calculated crossable gap threshold may therefore introduce a potential analysis bias: The probability of encountering a crossable gap, P(CG_ENC), may be lower than what would be perceived by a pedestrian who readily walks at a faster speed and therefore utilizes shorter gaps. Similarly, the probability of utilizing a crossable gap is expected to be high, given that the threshold for what is considered crossable is high for 85% of the general pedestrian population. Nonetheless, the chosen walking speed is considered a reasonable assumption in light of national policy documents like the MUTCD, and in light of the fact that the threshold is consistently applied to all sites to allow for a relative comparison. The same crossable gap definition is also proposed in Chapter 6, which talks about extension of the research results.

The combined effect of gap and yield availability and utilization is reflected in the delay experienced by pedestrians. Three delay performance measures are defined in the analysis:

- **Observed Delay per Leg (s):** The pedestrian delay in seconds, defined as the time difference between when the trial started and when the pedestrian initiated the crossing.



This figure shows an illustrative example of how pedestrian–vehicle events are determined in the NCHRP Project 3-78A analysis framework. The figure shows the hypothetical interaction of one pedestrian and 10 vehicles and translates the different yield and gap events into the performance measures discussed in this chapter. This process is described in detail in the text.

Figure 14. Graphical illustration of variable definitions with example (source: Schroeder and Rouphail 2010).

- **Minimum Delay (s):** The minimum theoretical pedestrian delay in seconds, defined as the time difference between when the trial started and when the first yield or crossable gap was encountered by the pedestrian.
- **Delay>Min (s):** The delay beyond the first opportunity, defined as the time difference between first yield or crossable gap encountered by the pedestrian and the actual crossing initiation.

The analysis further investigates two parameters that are intended to describe the efficiency with which a crossing opportunity is utilized for both gaps and yields:

- **Latency (s):** The latency is defined as the time between when the last vehicle went through the crosswalk and the time the pedestrian initiated the crossing.
- **Yield Lost Time (s):** The yield lost time (YLT) is defined as the time between when a driver first yields and the time the crossing is initiated. Note that in some cases, pedestrians may prefer to cross only after a car has come to a full stop (stopped yield), and so some inherent yield utilization time is expected.

Finally, the analysis uses the rate of O&M interventions that represent a measure of pedestrian safety during the crossings. The study participants were at all times accompanied by a certified O&M specialist who was directed to stop the participants if the crossing decision would have resulted in undue risk to pedestrian and/or driver. The resulting rate of O&M interventions is defined as follows:

- **Intervention rate (%):** The number of times the O&M specialist intervened for a particular participant divided by the total number of lanes crossed for a particular condition. For example, one intervention over a set of eight lane crossings at the roundabout entry corresponds to an intervention rate of 12.5%.

Most of the performance measures above are expressed as percentages, which could also be interpreted as a probability of a certain event taking place or a rate of occurrence of that event. For all percentage measures, the level of aggregation is on the level of the individual participant for all crossings by that participant at a particular location. For example, a pedestrian who crosses the entry leg of a roundabout four times will have an average rate of yield encounters calculated from those four crossing attempts. The same pedestrian will have a different rate of yield encounters for the exit leg crossing and also different entry and exit leg percentages for any additional approaches at the roundabout included in the study. The aggregation to the leg per participant level is necessary to ensure that the data point includes at least one of each event type (i.e., a crossable gap and a yield) and a range of outcomes (utilized and non-utilized). Data for a single crossing attempt are often characterized by scarce data, where only certain events are represented. Once the data are combined for all participants, the analysis reports the average, minimum, maximum, and standard deviation of performance at each crossing location.

The delay performance measures are measured in a temporal dimension (in seconds). For those measures, aggregation is again to the level of the single participant at one crossing location. But in addition to the average, minimum, maximum, and standard deviation, the analysis further reports the 85th percentile of the estimate. This is common practice for the analysis of continuous variables in traffic engineering applications such as delay studies (Institute for Transportation Engineers 1994).

Performance Measure Example

This section presents an illustrative example of the different performance measures used in the analysis, which was previously published in Schroeder and Rouphail (2010). The example in Figure 14 assumes a crossing attempt by a single pedestrian who encounters 10 different vehicles at a single-lane crossing.

Figure 14 shows a time line of a pedestrian encountering 10 hypothetical vehicle events. The time line proceeds from left to right, from the start of the trial until the last vehicle that interacted with the pedestrian crossed the plane of the crosswalk. Of the 10 vehicles, vehicles 2, 4, 7, and 8 yielded to the pedestrian, but none of these yields were utilized. Vehicles 1, 3, 5, 6, 8, and 9 didn't yield even though a pedestrian was waiting at the crosswalk. No yield information is available for vehicle 10 since the pedestrian had already walked across by the time it crossed the plane of the crosswalk. Consequently, the variable P(Yield) is calculated from 4 yields divided by a total of 9 drivers that could have yielded and equals 44.4%. On the contrary, the variable P(Y_ENC) = 40% is calculated by dividing 4 yields by a total of 10 vehicles encountered in the trial.

The temporal separation between vehicles 2–3, 5–6, and 9–10 constitute 3 crossable gaps, the last of which was utilized by the pedestrians. The gap from the start of the trial to vehicle 1 and the gaps between vehicles 4–5 and 8–9 were below the crossable gap threshold. The measure P(CG) = 50.0% is calculated by dividing 3 crossable gaps by 6 total gaps encountered. P(CG_ENC) = 30.0% is calculated by dividing 3 crossable gaps by a total of 10 events.

The advantage of the P(Y_ENC) and P(CG_ENC) measures is that they have the same denominator (total number of encounters) and are thus additive. This ensures a consistent and objective definition of events. In the NCHRP Project 3-78A analysis, these two variables are preferred and are used instead of P(Yield) and P(CG). The common denominator is further critical in the extension work described in Chapter 6.

The rates of yield and crossable gap utilization are calculated at $P(GO|Y) = 0.0\%$ and $P(GO|CG) = 33.3\%$, respectively. Delay is defined as the temporal duration from the time the trial starts until the pedestrian initiates the crossing. The minimum delay is less, calculated as the time spent waiting until the first crossing opportunity, which in this case is the yield by vehicle 2. Consequently, the Delay>Min is defined as the difference between delay and minimum delay.

Adapting the Framework to Two-Lane Crossings

The above framework was initially developed for single-lane approaches. For any crossing situation where the pedestrian only faces one conflicting lane, crossing opportunities are uniquely defined by the vehicle state in that lane (yield, crossable gap, or non-crossable gap). However, at a two-lane crossing, the analysis needs to consider the vehicle state in both lanes. The analysis of two-lane crossings therefore distinguishes between driver behavior in the **near lane** (the closest lane relative to the position of the pedestrian) and the **far lane**. Depending on the crossing location (entry/exit and curb/island), the near lane can be the inside or outside lane of the two-lane approach.

The analysis defines the vehicle state in the near lane in the same five event categories defined previously: rolling yield (RY), stopped yield (STY), forced yield (FY), crossable gap (CG), and non-crossable gap (non-CG). The vehicle state in the far lane will then be defined relative to the near-lane condition in the same five principal categories (RY, STY, FY, CG, and non-CG). Initially, this results in 25 possible combinations of the near/far-lane vehicle state.

Further, the near-lane events typically have some temporal dimension. For example, a crossable gap lasts a certain amount of time. Similarly, a yield has some duration associated with it that is related to driver patience and the responsiveness of the pedestrian. To adequately recognize this temporal dimension, a separate far-side category is introduced: multiple events. This category indicates that more than one event took place in the far lane during one near-lane event. For example, several cars could have passed the plane of the crosswalk in the far lane during one large gap in the near lane. For purpose of analysis, it is assumed that the last event in the multiple-event sequence governs the interaction. In total, the two-lane roundabout analysis thus considers five near-lane event categories and 10 far-lane categories (five single-event and five multiple-event categories) for a theoretical 50 possible event combinations (see Figure 15).

Since this high number of event classifications becomes unmanageable, the results in the main portion of the report combine all near-lane events in three categories (yield, crossable gap, and non-crossable gap) and do the same for far-lane events, thus simplifying the distinction between a single event or multiple events in the far lane substantially. With this aggregation, the number of near–far lane event combinations is reduced to nine (Figure 16). The results for the full event matrix are discussed in detail in Appendix A.

The nine event outcomes in Figure 16 can further be put into three categories that are themselves represented as probabilities:

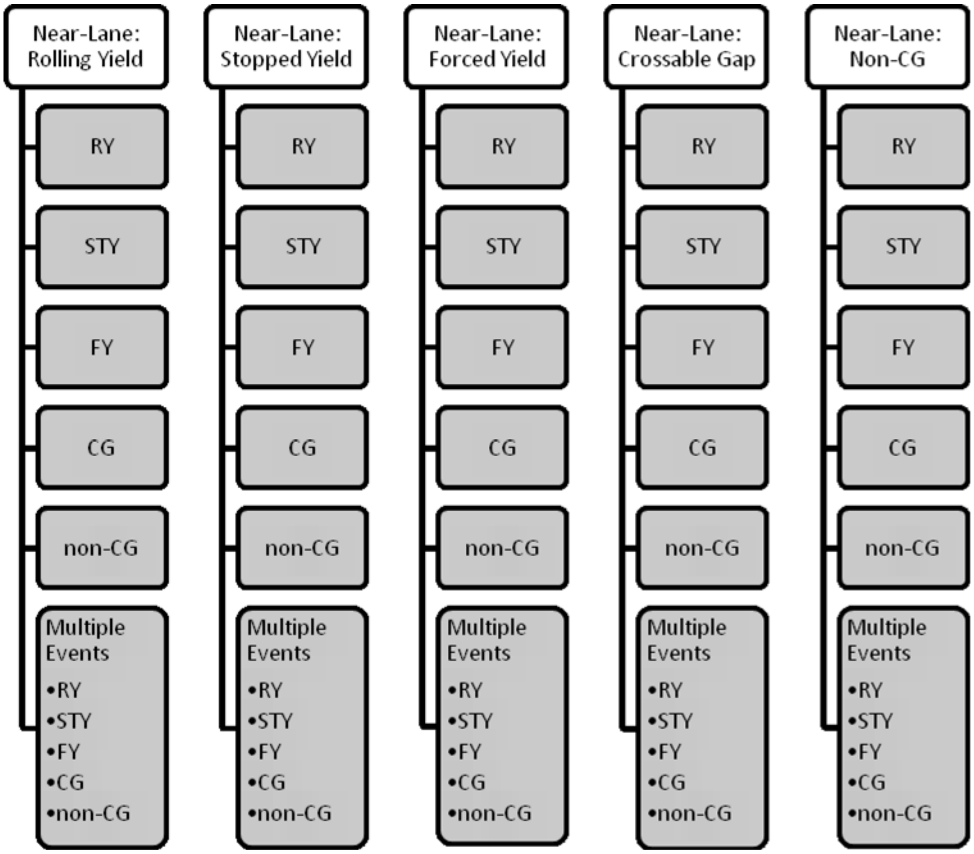
- **PA_Dual:** The likelihood of encountering a crossing opportunity in **both lanes**, including yield–yield, yield–CG, CG–yield, and CG–CG events, divided by the total of all events.
- **PA_Half:** The likelihood of encountering a crossing opportunity in **only one lane**, including yield–non-CG, CG–non-CG, non-CG–Yield, and non-CG–CG events, divided by the total of all events.
- **PA_None:** The likelihood of encountering a crossing opportunity in **neither lane**, including non-CG–non-CG events, divided by the total of all events

This stratification becomes important in light of identifying crossing opportunities and interpreting pedestrian utilization of these opportunities. Clearly, a crossing opportunity in both lanes corresponds to a valid crossing strategy. Similarly, if neither lane exhibits a crossing opportunity, the event clearly is non-crossable. If only one of the lanes exhibits a crossing opportunity, a conservative pedestrian would be expected to wait. A more assertive pedestrian may seize the crosswalk in hope of eliciting a driver response in, for example, the far lane. The utilization parameters associated with PA_Dual, PA_Half, and PA_None are denoted as PU_Dual, PU_Half, and PU_None, respectively. Definitions of the utilization measures are consistent with the single-lane analysis framework.

For the purpose of this analysis, it is assumed that only events with a crossing opportunity (either a yield or crossable gap) in *both lanes* represent valid overall crossing opportunities. Consequently, only those events will be included in the discussion of rates of encounter of crossing opportunities and their utilization. The definitions for delay and safety performance measures are the same as for single-lane crossings.

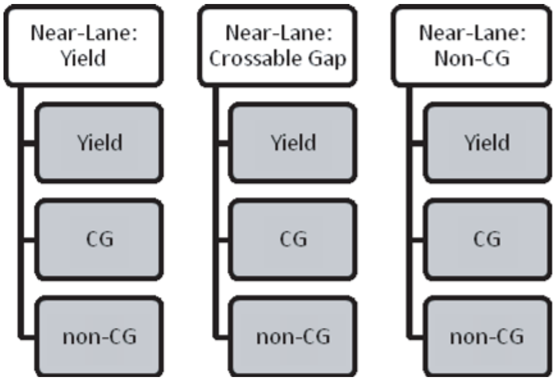
Research Hypotheses

The analysis framework hypothesizes that the performance measures above describe the most pertinent aspects of pedestrian–vehicle interaction at the test sites. The measures will be used in this research to quantify the operational differences between test sites and to contrast various crossings at the same site (for example, entry versus exit leg). More



This figure shows a diagram of all possible pedestrian–vehicle interaction events at a two-lane crossing. The figure shows five possible event states for the lane nearest the pedestrian: rolling yield, stopped yield, forced yield, crossable gap, and non-crossable gap. Each of these five event states can be associated with the same five event outcomes in the far lane. The far lane can further feature multiple event outcomes, which in turn are classified by the five categories. In total, the figure shows 50 possible event combinations.

Figure 15. Full matrix of near-lane and far-lane event combinations.



This figure shows a diagram of the condensed matrix of pedestrian–vehicle interaction events at a two-lane crossing. The figure shows three possible event states for the lane nearest to the pedestrian: yield, crossable gap, and non-crossable gap. Each of these three event states can be associated with the same three event outcomes in the far lane for a total of nine event combinations.

Figure 16. Condensed matrix of near-lane and far-lane event combinations.

importantly, it is hypothesized that the performance measures are sensitive to the installation of pedestrian crossing treatments (Schroeder and Rouphail 2007). Each treatment is intended to improve one or more of the performance measures.

In particular, a treatment that is primarily geared toward improving driver awareness of the crosswalk and the presence of the pedestrian is expected to increase the likelihood of encountering a yield, P(Y_ENC). Yielding behavior is likely also affected by the speed of the vehicle (Geruschat and Hassan 2005), and consequently any traffic calming treatment is likely to increase yielding behavior. The rate of yielding or stopping for pedestrians is expected to increase to very high levels for any treatment that shows a solid red indication to drivers (Fitzpatrick et al. 2006), which includes the PHB or HAWK signal.

The availability of crossable gaps is primarily a function of traffic volume, where higher volumes will decrease the availability of crossable gaps. Any upstream metering of traffic through, for example, a signal will also increase the availability of crossable gaps as it bunches traffic in platoons. The downside of vehicle platooning is that it has been linked to a lower propensity to yield (Schroeder 2008).

The ability or willingness to utilize yields, P(GO|Y), may be improved by lower ambient sound levels or an amplification of the noise of the approaching vehicle. The sound-strip treatment attempts to do the latter in that it auditorily distinguishes the conflicting traffic stream from the general background traffic (Inman et al. 2005). The willingness to utilize a yield may further be affected by any treatment that gives the pedestrian confirmation in the form of an audible message (APS device or other audible information device) or that slows traffic down to make the pedestrian more comfortable interacting with traffic.

The ability or willingness to utilize crossable gaps, P(GO|CG), is also expected to be correlated with the relative noise of conflicting traffic to the overall level of ambient noise. Again, the sound-strip treatment is hypothesized to help in this regard in that the absence of sound cues corresponds to a potentially crossable gap. An upstream signal that meters overall traffic on the approach may generate "all-quiet" periods during which a blind pedestrian can more reliably identify a crossable gap.

For the treatments tested, the following hypotheses are made:

- Flashing beacon: Increase P(Yield) and P(GO|Y),
- Sound strips: Increase P(GO|Y) and P(GO|CG),
- Raised crosswalk: Increase P(Yield) and P(GO|Y), and
- Pedestrian hybrid beacon: Increase P(Yield) and P(GO|Y).

Further, the occurrence of crossable gaps, P(CG), is likely to vary across sites and study participants depending on traffic volumes and the time of day of the study. Ultimately, the four probability terms are hypothesized to affect the delay experienced by the pedestrians. An increase in one or more of the probability terms is expected to decrease the experienced delay as more crossing opportunities are available and/or utilized.

The hypothesized impact on pedestrian safety is more difficult to define. For example, one would generally expect that a PHB would create more frequent and safe crossing opportunities. However, experience at pedestrian signals (Fitzpatrick et al. 2006) shows that driver compliance may be less than 100%. Consequently, reliance on the audible device message from the signal may contribute to additional risk. In this study, participants were generally instructed to not solely rely on the APS message but to always use their own judgment and audible perception of the traffic environment. In principle, the research hypothesizes that any of the treatments will contribute to reducing pedestrian delay and enhancing safety. However, it is recognized that the safety performance evaluation may deliver mixed results.

CHAPTER 5

Results

This chapter is devoted to the results of the field trials with blind study volunteers at the selected treatment sites. It presents a summary of findings that are most pertinent to the understanding of the specific crossing challenges at the site, as well as the effect of the installed crossing treatments. Appendix A contains more detailed results for each site, and the reader is encouraged to refer to that material for a more in-depth discussion. The results are presented sequentially for channelized turn lanes, single-lane roundabouts, and two-lane roundabouts. The analysis uses the analysis framework, event definitions, and performance measures defined in Chapter 4. The chapter concludes with a summary comparison of all field trials and some discussion items related to the results.

Channelized Turn Lane

Study Overview

The field study at the CTL location focused on two crossing treatments. The treatments were (1) sound strips (SS) that were intended to increase the awareness of pedestrians of approaching vehicles and (2) sound strips in combination with a pedestrian-actuated flashing beacon (FB) that was intended to increase driver yielding behavior. In the following discussion, the crosswalks will be identified by treatments installed as SS-ONLY and SS+FB, respectively. Both turn lanes were further supplemented with lane delineators that were intended to prevent late merges into the turn lane. All treatments, including the lane delineators, were installed between pretest and posttest. A more detailed description of the site and treatments is given in Chapter 3.

Crossing Performance Results

The evaluation of pedestrian crossing performance used the measures defined in Chapter 4: the availability of crossing opportunities in the form of yields and crossable gaps, the rate of utilization of these opportunities, pedestrian delay, and the rate of O&M interventions.

The field evaluation at the CTL location generally showed that participants experienced significant delay and risk. Despite the fact that only a single lane needed to be crossed, the combination of background noise at the busy intersection and high approach speeds in the turn lane caused high delays and frequent interventions. A comparison of the two crossing locations in the pretest did not show significant differences for most of the measures, giving confidence that the two locations allow for a valid comparison of the different treatments installed. The starting order of participants was randomized as to which crossing they started on. No consistent and significant differences were identified between crossing attempts from the curb versus from the island, although some participants stated that crossing from the island was harder due to the traffic noise behind them.

The pretest study was completed in May 2008, and a total of 16 blind travelers participated. Fourteen of the original 16 participants returned for the posttest study in November 2008. The treatments were installed in early October 2008, allowing six weeks for driver adaptation.

Sound-Strips-Only Treatment (SS-ONLY)

Table 1 summarizes the crossing performance for the CTL crossing that only had sound strips and lane delineators installed. The figures were obtained by averaging the mean crossing performance of each of the study participants at this location.

Table 1 shows that the installation of the sound strips by themselves did not have a large or significant impact on yield and CG crossing opportunities. This confirms the underlying research hypothesis since the treatment was primarily intended to aid with the utilization of opportunities. The probability of utilizing a yield surprisingly decreased from 50.8% to 40.5%, although this difference was not statistically significant. A closer

Table 1. Crossing performance summary, pretest and posttest, at SS-ONLY CTL.

Performance Measure	Pre	Post	Difference	p-value
Yield Opportunities	18.40%	18.60%	0.20%	0.2728
CG Opportunities	34.90%	41.20%	6.30%	0.1666
Yield Utilization	50.80%	40.50%	–10.30%	0.2878
CG Utilization	60.30%	68.20%	7.90%	0.4238
Average Delay (s)	26.2	18.5	–7.7	0.1898
Delay>Min (s)	15.6	11.7	–3.9	0.4224
85th Percentile Delay (s)	40.9	32.7	–8.2	–
O&M Interventions	9.40%	2.9%	–6.5%	0.0204

look at the yield utilization illustrates that the percentage of yield events that were forced by the pedestrian decreased from 11.3% to 6.4% (not shown in Table 1 but discussed in Appendix A). A forced yield occurs when a pedestrian steps out onto the roadway prior to the driver initiating the yielding process. The degree of risk associated with these events depends on the relative position and speed of the vehicle at the time of crossing initiation. Forced yield events should therefore not necessarily be interpreted as poor or risky decisions. However, the reduction in the occurrence of forced yields (though not significant) may suggest that the sound strips were successful in assisting the pedestrians to distinguish yielding and non-yielding vehicles. However, this hypothesis should be confirmed with additional research with this treatment.

The SS-ONLY treatment further increased the rate of crossable gap utilization by approximately 8%. However, similar to other measures, this increase was not statistically significant. In general, all observed measures experienced a large degree of variability across participants, making it challenging to statistically validate small changes in a performance measure. Overall, the installation of the sound strip and lane delineator treatments at the SS-ONLY turn lane did not have a large impact on most of the availability and utilization performance measures when aggregated for all participants. The treatments did seem to reduce the average and 85th percentile pedestrian delay, as well as the delay over minimum. Similar to the effects above, these decreases were not statistically significant but suggest promise for the sound strips with some modifications or in combination with another treatment.

This CTL crossing had the highest observed occurrence of interventions of any of the test locations, with the highest intervention rate per participant reaching 30% (six interventions in 20 crossings). The pretest intervention rate corresponded to 30 individual interventions recorded among 10 of the 16 participants. Of these 30 interventions, seven were associated with a stopped car on top of the crosswalk. For these cases, vehicles were queued back from the downstream merge point and did not leave the crosswalk unoccupied. Participants seemingly were not able to hear the fact that a car was stopped due to the high ambient noise at the busy intersection. For the remaining 23 interventions, vehicles were moving and therefore represented situations were a potential collision would have been more severe.

After treatment installation, only eight interventions were observed for five of the 14 posttest participants. This corresponds to a significant reduction of O&M interventions, from 9.4% to 2.9%, which is noteworthy and further establishes that the treatment has some potential. The reduction of interventions supports the hypothesis that the sound-strip treatment improved the ability of the study participants to audibly interpret the vehicle patterns in the turn lane. However, even an intervention rate of 2.9% remains risky, as it corresponds to one potentially dangerous event in 34 crossing attempts. In the pretest condition the intervention rate corresponded to a risk chance of approximately one in 11 crossing attempts.

The analysis does suggest that additional treatments may be necessary at this location, due to a combination of high volumes, high speeds, background noise, and driver disregard of crosswalk laws and pedestrians.

Sound Strip plus Flashing Beacon Treatment (SS+FB)

Table 2 summarizes the crossing performance for the CTL crossing that had sound strips, lane delineators, and a pedestrian-actuated flashing beacon installed. The figures were obtained by averaging the mean crossing performance of each of the study participants at this location. No consistent and significant differences were identified between crossing attempts from the curb versus from the island.

As hypothesized, Table 2 shows that the supplemental installation of the flashing beacon resulted in an increase in yielding from 15.2% to 22.0%. While statistically significant, the resulting posttest yielding rate of 22.0% is still considered low. The observed yielding rate with the flashing beacon installed is generally within the range of findings from a national survey of the yield performance of overhead flashing beacons at unsignalized midblock crossings (Fitzpatrick et al. 2006).

Table 2. Crossing performance summary, pretest and posttest, at SS+FB CTL.

Performance Measure	Pre	Post	Difference	p-value
Yield Opportunities	15.20%	22.00%	6.80%	0.0363
CG Opportunities	44.70%	49.20%	4.50%	0.444
Yield Utilization	53.10%	64.60%	11.50%	0.2769
CG Utilization	63.20%	89.30%	26.10%	0.0011
Average Delay (s)	23.4	12.2	–11.2	0.0453
Delay>Min (s)	14.9	4.9	–10.0	0.0342
85th Percentile Delay (s)	38.6	17.9	–20.7	–
O&M Interventions	5.6%	1.40%	–4.2%	0.0112

In a synthesis of results from 17 sites, the authors recorded an observed range in the average yielding rates of from 13% to 91%, which suggests that other contributory factors (speeds, driver population, regional differences) affect yielding behavior.

Consistent with the research hypotheses, the treatment did not have a significant impact on the availability of crossable gaps. The rates of utilization for yield and crossable gap opportunities both saw a significant increase of 11.5% and 26.2%, respectively. Only the CG utilization is statistically significant, but both trends are surprising in light of the fact that the SS-ONLY treatment did not show the same results. A possible explanation is proposed: It is hypothesized that the auditory message that accompanied the flashing of the beacon gave pedestrians additional confidence. The primary intent of the treatment was to alert the approaching driver to the pedestrian's crossing intent and increase yielding. However, the audible message provided an auditory confirmation to the pedestrian that the beacon was flashing and appears to have contributed in some way to the willingness of pedestrians to utilize crossing opportunities. However, it's not clear that the pedestrians were able to confirm the opportunity auditorily. The O&M specialist who was monitoring participants was concerned that the auditory message masked some vehicular sounds and could encourage crossings that were more risky because some participants seemed to rely more on the vehicles yielding, without confirmation, when the flasher was present.

In the tested combination, the SS+FB treatments had a large effect on the pedestrian delay as well as a reduction in O&M interventions. Average delay and the delay over minimum were both reduced significantly, by 10–11 s, and the 85th percentile delay was reduced by over 20 s. O&M interventions were reduced significantly, from 5.6% to 1.4%, which reduced the likelihood of a potentially dangerous event from one in 18 decisions to one in 71. The raw count of interventions was 14 in the pretest and four in the posttest conditions, and both counts are lower than at the SS-ONLY crossing. It is unclear what the specific reason for this difference in interventions is between the two crossing locations. Of the 14 pretest interventions, only one was associated with a stopped car on the crosswalk, while the SS-ONLY crossing resulted in seven of these events. Given that the two locations had similar traffic volumes and that the starting order for participants was randomized, a likely contributory explanation for the difference in intervention rates is related to sound patterns at the crossing.

Appendix A gives additional results for the CTL crossings and treatments, including a discussion of inter-participant variability.

Participant Feedback

Following each of the pretest and posttest studies, participants were asked a series of questions about their perceptions of the crossing and their level of confidence in their crossing decisions. The blank survey forms are provided in Appendix G. While participants seemed somewhat more confident during the treatment conditions, their feedback generally indicated some uncertainty in crossing at the CTL locations. However, this level of uncertainty didn't seem to quite reach the level that may be expected from the high delay and intervention rates at this site. The average of the responses on the confidence question ("How would you rate your confidence in your ability to cross here safely on a scale of 1 to 5, with 1 being not at all and 5 very confident?") was 3.66 in the pretest, and 4.0 and 4.1 in the SS-ONLY and SS+FB posttests, respectively.

These numbers seem to indicate a false sense of participant confidence in their ability, if measured by the rate of interventions. One participant who rated her confidence in crossing safely at 4 said: "but maybe it's too dangerous. I knew you were behind me to grab me." Another said: "It's a little risky; I could make mistakes." Although the team instructed participants to cross only if they would do so if they were alone, without an O&M specialist, it seemed that they felt they should try to cross to help us in our research. Participants repeatedly were reminded that even the fact that they reached the 2-min timeout or decided not to cross were valuable research findings. However, all participants attempted to cross and very few people actually timed out. It is possible that the 2-min time limit was longer than participants were willing to wait.

While participants said yes in the CTL pretest to a question about whether they would use these crossings if they were on the route home from work (14 yes, 2 no), their responses often had qualifying remarks such as one person who said yes, then added "but I'd probably try to find another way, but most of the corners around here are like this." In the SS-ONLY and the SS+FB conditions, the responses were roughly the same, with 10 yes, 3 no, and 1 no answer in the SS-ONLY and 9 yes, 2 no, and 3 no answer in the SS+FB condition.

From the pretest, the participants' responses to the question "Do these crossings need anything to increase safety and usability? If so, what would you suggest?" may provide more insight into their confidence than their ratings on the confidence question. Unlike the responses at the Charlotte single-lane roundabout (same city and some of the same participants), almost everyone made a suggestion regarding detecting gaps or yields, which included:

- "Tripper that lets you know that cars are coming, like old gas station tubes";
- "Better indications to the drivers to yield, or a cop to bust people for not yielding";
- "Flow indicators like a signal box to tell you if something is coming, but have to know how fast though so not sure how well that would work";
- "Audible signals to tell me when to cross, but don't know how that would be done for the whole thing though because that would delay traffic";
- "Would be helpful to have auditory cue that cars were rolling across further down the lane, like a single speed bump or something";
- "Something to make them slow down";
- "Modify to push button to change light and make them stop for that lane too; very short sound/message to know its working"; and
- "Audible signal that lets you know when cars are yielding; can't trust them all to stop for you."

To the same question in the posttest, several individuals responded very positively to the sound strips, mainly suggesting that the sound strips needed to be louder and more consistent in providing a sound when vehicles were moving at a slower speed. An interesting comment from one individual was that she was more confident in the pretest, but she'd realized during the posttest that she'd just not heard some of the cars the first time. In the SS condition, she heard the vehicles approaching from further away and realized that she'd been stepping out in front of cars in the channelized lane in the pretest condition. This realization was accurate and matches the performance data for this participant. In the pretest, a car sometimes entered the CTL just as this participant started crossing. Since she walked very quickly, and since drivers noticed her, she was able to complete most of these crossings in the pretest without an intervention. In this participant's case, the delay went up in the SS-ONLY posttest, attributed to a self-diagnosed increased awareness of traffic patterns due to the sound strips.

Another interesting issue is that eight participants said they could hear better to make crossing decisions from the curb as opposed to from the island. They stated that the sound of traffic behind them made the crossing decision more difficult when waiting on the island. That is an interesting point because it is expected that pedestrians are more visible to drivers when on the island because drivers are predominantly focusing to their left and on the traffic they will be merging into.

Several participants also commented that they could hear the sound strips better on the SS-ONLY corner than they could on the SS+FB corner. This was also noted by the O&M specialist and other members of the research team. From the testing it is unclear what caused this perceived sound difference. Traffic volumes (and presumably noise) were higher at the SS-ONLY corner, which suggests that the perceived sound difference is unlikely to be traffic related. One possible explanation is the fact that the SS-ONLY approach was on a slight down slope in the approach of the crosswalk, while the SS+FB corner was on an upslope. Assuming that sound is projected horizontally as vehicles traverse the sound strips, the SS-ONLY sound waves would be projected more directly toward the participants' ears. Due to the upslope at the SS+FB crosswalk, the sound waves would be projected toward the pavement, which may have contributed to the perceived difficulty of hearing the sound strips at that approach.

Participants in the posttests were asked several questions about the sound strips and about the push-button locator tone and audible information on the flashing beacon (Table 3). For these questions, participants were asked to rate the extent of their agreement, with 1 being strongly disagree and 5 strongly agree.

The questions about the sound strips were about both corners, so the problems some participants had in hearing the strips on the southeast corner can be expected to have influenced their ratings. Two qualified their responses about the sound strips by "when I could hear them." Others commented on not hearing slower cars on the strips. Overall, the responses to the treatments were mixed, as was noted in the performance measures.

Impact on Vehicular Traffic

The channelized turn lane enabled vehicular traffic to bypass the busy intersection of a four-lane and a six-lane arterial. Both CTL locations featured long 275- and 300-ft deceleration lanes measured from the beginning of the crosswalk. These allowed right-turning traffic to avoid any through-movement queues

Table 3. Participant responses to treatment effectiveness at CTL.

Rating questions	Average of responses (N=13) 1=strongly disagree, 5=strongly agree
The sound strips helped me know when vehicles were approaching.	4.38
The sound strips helped me know when vehicles were slowing down.	3.54
The sound strips helped me know when vehicles had yielded.	2.92
The sound strips made me confident that I was starting to cross at a safe time.	3.46
Where there were beacons installed, I'd push the button each time I wanted to cross.	4.08
Knowing the beacon was flashing made me more confident that I was starting to cross at a safe time.	3.83
The speech message didn't interfere with my ability to hear traffic.	4.33
The locator tone on the beacon helped me know I was coming to the crosswalk.	3.77
The locator tone helped me go straight across the crosswalk.	2.64
The locator tone helped me know I was approaching the end of the crosswalk.	2.83

that may have formed at the main intersection. Consequently, the average CTL vehicle delay (in the absence of pedestrians) was low compared to other movements, and drivers expected largely free-flowing operations.

The observed vehicle free-flow speeds in the pretest condition were high at both CTL locations, with an average 32.8 mph upon entering the turn lane and 21.5 mph as vehicles crossed the plane of the crosswalk, determined from laser speed measurements. The crosswalk speeds were lower during signal phases that resulted in traffic moving downstream of the CTL (opposing left-turn and cross-street through phases). During those phases, average free-flow speeds at the crosswalk were 18.5 mph, while the average during other phases was 22.4 mph ($p < 0.0001$). This difference points to the fact that drivers are well aware of downstream traffic conditions. This behavior further causes concerns regarding driver attentiveness to pedestrians at the crosswalk since the distance between the back of the crosswalk and the downstream merge point is only approximately 50 ft. It is one possible explanation for the low observed yielding rate at this site.

With the installation of the sound strip and flashing beacon treatments, no significant effects on speeds were detected in most segments of the turn lanes. A slight increase in speeds was measured just upstream of the crosswalk (increase from 21.5 to 22.5 mph, $p = 0.0536$), but this change is not considered to be a notable impact on driver behavior. Generally, no large queuing impacts were detected as a result of drivers yielding to pedestrians. In some cases, queues from the downstream merge point spilled back across the crosswalk in both pretest and posttest conditions, resulting in a few crossing attempts in between stopped cars. In several instances, participants were not aware of a stopped vehicle on the crosswalk, resulting in O&M interventions as discussed above. Given the low yielding behavior, the pedestrian presence and treatment installation were not considered to have a notable effect on traffic operations.

Single-Lane Roundabout

Study Overview

The scope of NCHRP Project 3-78A originally included only one single-lane roundabout site for a pretest and posttest study, consistent with other locations. However, following the pretest, the research team was directed not to pursue with treatment installation and a posttest at the site. The site was not considered suitable for treatment installation due to participant responses, low intervention rate, and low traffic volumes during the pretesting. Consequently, the research funds were reallocated to revisit available video data collected at a single-lane roundabout in Raleigh, NC, and to study an additional single-lane roundabout in Golden, CO. The prior data collection at the Raleigh site was comparable to the NCHRP Project 3-78A studies since the same general data collection protocol was used. The Golden site was selected for supplemental study due to its proximity to the studied two-lane roundabout. The site was studied twice (concurrent with the two-lane roundabout pretest and posttest), yet no treatments were installed. This approach served two objectives: (1) the ability to compare the crossing ability of the same participants at a single-lane and two-lane roundabout, and (2) to test for a learning effect of the same participants repeating the study without any treatment installation.

This section presents the crossing performance results sequentially for all three locations. It then discusses the impact on vehicle traffic and a summary of participant survey responses concurrently for all three locations.

The Charlotte, NC, single-lane roundabout (DAV-CLT) was studied in the fall of 2007, and data from a total of 10 blind participants were used in the analysis. Even though there were a total of 19 participants in the study, the remaining data were not available for analysis due to video malfunction. For the

Golden single-lane roundabout, the pretest was completed in July 2008 with a total of 18 blind travelers (GOL-PRE). Thirteen of the original 18 participants returned for the posttest study in September 2008 (GOL-POST). Again, no treatments were installed at this roundabout, so the underlying hypothesis is that overall performance in pretest and posttest conditions is the same. The Raleigh site was originally studied in a separate research project (NIH 2010) in 2004, with video recordings reanalyzed as part of this project using the NCHRP Project 3-78A analysis framework (PS-RAL). The analysis included a total of 12 blind study participants.

Appendix A gives additional results for these locations, including a discussion of between-participant variability.

Crossing Performance Results

Charlotte, NC, Single-Lane Roundabout

The field evaluation at the Charlotte single-lane roundabout location (DAV-CLT) yielded mixed results. On the one hand, participants experienced very little risk in terms of O&M intervention rates; on the other hand, delays experienced by the participants were high. Table 4 summarizes the crossing performance for the DAV-CLT site. The figures were obtained by averaging the mean crossing performance of each of the study participants at this location.

Table 4 shows a very low occurrence of yield opportunities at only 6.3%. The rate of encountering crossable gaps was higher, at 28.8%, which is explained by generally low traffic volumes at the site except for some peak-hour traffic surges. The rate of utilization of both yields and crossable gaps was about two thirds of all encounters, suggesting that despite low volumes and associated low levels of ambient noise, participants had some difficulties at this location. From the rate of utilization it is unclear whether these opportunities were missed (i.e., the pedestrian failed to detect them) or rejected. In fact, several participants indicated that they were aware of the presence of, for example, a yielding vehicle, but nonetheless chose to wait. At low conflicting volumes, the additional wait time was generally rewarded by an all-quiet period that made crossing very comfortable.

Table 4. Crossing performance summary at DAV-CLT.

Performance Measure	Mean	Std. Dev.
Yield Opportunities	6.3%	4.9%
CG Opportunities	28.8%	6.8%
Yield Utilization	67.4%	42.3%
CG Utilization	63.3%	19.3%
Average Delay (s)	25.3	13.8
Delay>Min (s)	18.0	12.8
85th Percentile Delay (s)	35.4	–
O&M Interventions	0.8%	2.6%

This type of behavior may further explain why the observed delay was relatively high at an average of 25.3 s. The delay over minimum was also high, at 18.0, due the aforementioned inefficiency in utilizing crossing opportunities. The 85th percentile delay was expectedly even higher at 35.4 s. Further, these delay figures mask the fact that some pedestrians experienced even higher delays. The maximum average delay experienced by a single pedestrian was 74.0 s over 12 trials. The maximum average delay over minimum was 59.4 s.

The site further exhibited an overall low rate of O&M interventions. In fact only two interventions were observed over the 120 crossings at the entry and exit leg, corresponding to the stated rate of 0.8%. The two interventions (one at entry and one at exit) were recorded for two different participants. The remaining participants therefore did not experience any interventions at this site.

This analysis points to mixed results in terms of the question of roundabout accessibility. Clearly, a low intervention rate speaks to a safe crossing. However, the elevated levels of delay are indicative of significant inconvenience for pedestrians who are blind and further may lead people to avoid this crossing location. A further cause for concern is that traffic volumes may increase and reduce the availability of crossable gaps while presumably increasing the level of ambient noise. It is unclear whether yielding behavior would be affected with higher volumes or would stay the same. As discussed, no treatments were tested at this location, but at higher volumes, a treatment intended to increase driver awareness and propensity to yield may be appropriate.

Raleigh, NC, Single-Lane Roundabout

The field evaluation at the Raleigh single-lane roundabout location (PS-RAL) was intended to test the hypothesis that the findings at the DAV-CLT site were biased by low conflicting traffic volumes. The PS-RAL exhibits higher traffic volumes and is further located in a campus environment with more frequent pedestrian activity. It was hypothesized that driver expectations of encountering pedestrians would be elevated, which would result in an increased propensity to yield. Table 5 summarizes the crossing performance for the PS-RAL site. The figures were obtained by averaging the mean crossing performance of each of the study participants at this location.

Table 5 in fact shows a relatively high occurrence of yield opportunities at 33.0%. The rate of encountering crossable gaps was lower than at DAV-CLT, at 19.1%. Combined, over half of all vehicle encounters corresponded to crossing opportunities. At higher traffic volumes, this results in relatively frequent crossing opportunities over time. The rate of utilization of yields was very high at this site, at 85.4%. This may be explained by

Table 5. Crossing performance summary at PS-RAL.

Performance Measure	Mean	Std. Dev.
Yield Opportunities	33.0%	16.6%
CG Opportunities	19.1%	9.2%
Yield Utilization	85.4%	17.3%
CG Utilization	57.8%	34.4%
Average Delay (s)	11.1	7.8
Delay>Min (s)	5.8	6.4
85th Percentile Delay (s)	19.6	–
O&M Interventions	3.9%	5.8%

slower speeds that result in an overall reduced level of ambient noise. The rate of crossable gap utilization was just below 60%, which is in the same region observed at the DAV-CLT site.

A combination of frequent crossing opportunities and high utilization rates expectedly results in relatively low delay estimates. The average delay was 11.1 s, and the delay over minimum was only 5.8 s. The 85th percentile delay was somewhat higher at 19.6 s. As with other sites, individual participants experienced higher average delays, with the maximum average observed delay at 34.2 s (24.7 s delay over minimum).

However, the site exhibited a higher rate of O&M interventions, at 3.9%. This rate corresponds to a total of 15 interventions, 11 of which were observed at the exit portion of the crossing. The interventions were further distributed across nine of the 12 participants, suggesting that some risk was evident for most of the participants. One participant experienced five interventions across 32 crossing attempts, equivalent to a rate of 15.6%. In interpretation of these intervention statistics, it is important to highlight that a different O&M specialist accompanied the participants in this prior study. Therefore, while the experimental protocol was generally the same, it is possible that individual differences of the O&M specialist contributed to the difference in interventions.

The analysis shows the opposite trend of the previously studied DAV-CLT site. Due to the relatively frequent availability of yields and good utilization of crossing opportunities, the observed delays at PS-RAL were relatively low and further do not seem too different from what a sighted pedestrian might have experienced (see Delay>Min). However, the crossing decisions were characterized by a high intervention rate, which raises concerns for pedestrian safety. Since this study was performed as part of a different research project, no treatments were tested.

Golden, CO, Single-Lane Roundabout

The Golden single-lane roundabout was studied concurrently with a nearby two-lane roundabout. Two rounds of field testing were performed at the same time as the single-lane roundabout pretest and posttest treatment conditions. Even though no treatments were installed at the two-lane roundabout, the two test phases are referred to as GOL-PRE and GOL-POST, respectively. Table 6 summarizes the crossing performance for the site. The figures were obtained by averaging the mean crossing performance of each of the study participants at this location.

Table 6 shows no significant differences in the operational and safety performance during the pretest and posttest conditions. It can therefore be concluded that no measurable participant learning effect took place between the two studies and further that driver behavior and traffic patterns were similar. Both conditions showed a high occurrence of yield opportunities (over 40% of vehicle encounters) along with some crossable gap opportunities (over 20%). The utilization rates for both yields and crossable gaps were high, at or above 80%. As a result, the average delay experienced by participants was low (around 12 s), and only a very small portion of that delay was due to missed opportunities (delay over minimum was about 3 s). The variability in delay was higher at this site, and the highest average delay experienced by a participant was 51.4 s.

The intervention rate shows an apparent drop from 1.4% to 0.5% between pretest and posttest conditions, but this slight difference is not significant. Overall, five interventions were recorded, four of which occurred in the pretest condition.

Table 6. Crossing performance summary at GOL-PRE and GOL-POST.

Performance Measure	Pre	Post	Difference	p-value
Yield Opportunities	40.4%	43.8%	3.4%	0.6398
CG Opportunities	23.5%	21.3%	–2.2%	0.5800
Yield Utilization	79.4%	84.7%	5.3%	0.4897
CG Utilization	85.1%	81.2%	–3.9%	0.6368
Average Delay (s)	11.9	12.1	0.2	0.9544
Delay>Min (s)	2.8	3.1	0.3	0.8156
85th percentile Delay (s)	22.2	21.7	–0.5	–
O&M Interventions	1.4%	0.5%	–0.9%	0.2651

There may be some evidence that participant decision making in terms of risk taking improved; however, this claim is not supported by the other performance statistics (mostly the utilization rates). Since interventions are very rare events, it is likely that this apparent reduction is the result of random variability in this measure.

At the PS-RAL and DAV-CLT single-lane crossings, the queues that formed behind the yielding driver were safely contained behind the stopped car. However, a wide exit lane at the Golden single-lane roundabout caused some drivers to overtake the stopped car, creating a multiple-threat situation for the pedestrian. This behavior was also observed in relation to buses stopped at a downstream bus stop at this exit-lane crossing. While the intervention rate at this roundabout was low, this particular aspect of driver behavior causes concern for pedestrian safety. The issue of multiple-threat situations, where a near-lane yielding vehicle blocks the visual (and auditory) connection between the pedestrian and a far-lane driver, was hypothesized for two-lane roundabouts. Due to the wide lane widths, it also proved a concern at this exit-lane crossing. No multiple-threat events were observed at the entry leg.

The findings from the GOL-PRE and GOL-POST studies first and foremost give confidence that any observed treatment effect at the nearby two-lane roundabout was largely unrelated to a participant learning effect. Since the same participants performed the studies at both sites, the lack of an effect at this single-lane location supports the notion that the tested two-lane treatments indeed improved the crossing task, as is discussed below.

In comparison with the other single-lane roundabouts, the GOL-PRE/POST site exhibits similar performance to the PS-RAL site in the accessibility criteria of crossing opportunities, opportunity utilization, and delay. However, its safety performance is more similar to the DAV-CLT site, with a generally low intervention rate. Overall, this site appears to be the most accessible of the three tested single-lane roundabouts with low delay and risk.

Participant Feedback

Following each of the single-lane roundabout studies, participants were asked a series of questions about their perception of the crossing and the level of comfort in their crossing decisions. Participant feedback from the Raleigh roundabout was not available to the research team. The blank survey forms for the Charlotte and Golden roundabouts are provided in Appendix G.

Feedback from the Charlotte and Golden single-lane roundabouts indicated that participants generally felt comfortable with the crossing task at those locations in each round of testing. The average of the responses on the confidence question ("How would you rate your confidence in your ability to cross here safely on a scale of 1 to 5, with 1 being not at all and 5 very confident?") was 4.40 in Charlotte, 4.41 for the Golden pretest, and 4.46 for the Golden posttest. While Golden participants seemed more confident to the research team at the single-lane location in the posttest round, that impression was not supported by the participant survey results.

On the question "Would you use these crossings if they were on the most direct route home from work?" (slightly different wording in Charlotte), nine participants said yes and one said "no, would find another way" in Charlotte; for the Golden pretest 15 said yes, one no, one "maybe, depending on time of day," and one did not answer that question; and in the Golden posttest, all 12 said yes, including one who had said no in the Golden pretest.

In Charlotte, participants were asked about yielding vehicles and their reasons for crossing or not crossing when vehicles had yielded. (This question was not separated from the question about cues used for crossing in the Golden debriefing questionnaires.) Most comments indicated that participants found it difficult to decide if the drivers were yielding for them or something else (possibly other vehicles at entry lanes) and were concerned about how long drivers would stay stopped. Some stated that they waited for a person to actually roll down the window and talk to them before they would cross in front of a yielding vehicle. Some said they were unaware that a vehicle had yielded until after they had completed their crossing and heard the vehicle move behind them. In other words, they had not heard the vehicle at all and thought they were crossing in a gap in traffic.

In response to a question about modifications that might be needed to improve accessibility, the main concerns were with wayfinding, although a couple of participants suggested a signal of some sort to indicate when vehicles had yielded. Several said the roundabout was pretty accessible as is, or that it didn't need anything. The Charlotte participant who said she wouldn't use the crossings stated that she was still confused about finding the crosswalks and lining up correctly and not so concerned about the traffic and crossing. Golden participants commented on the narrow splitter island and the fact that no detectable warnings were installed. These geometric features raised concerns about being sure they stopped on the island before crossing the next lane of traffic.

Impact on Vehicular Traffic

Since no treatments were tested at the single-lane roundabouts, any impact on vehicle traffic is strictly attributable to the normal interaction between pedestrians and drivers. While no formal delay studies were performed at these locations, the research team noted no significant queuing impacts that resulted from the presence of the blind study participants.

The largest pedestrian-induced vehicle delay impact was evident at the PS-RAL site due to a combination of high traffic volumes and frequent background pedestrian (student) traffic. Background pedestrian traffic was present at all three locations but was much lower at the other two. Thus, the overall delay impact is marginal relative to vehicle delay upon entering the roundabouts.

At all locations, the team would occasionally observe a determined yielding driver, who would wait 10 or more seconds to allow the pedestrian to cross, which would then cause some vehicle delay. Any queues that formed as a result of pedestrian presence dissipated quickly once the pedestrian was out of the crosswalk. In fact, buses that stopped downstream of the exit portion of the tested crosswalks at PS-RAL and DAV-CLT frequently caused more significant queuing than the pedestrians.

Two-Lane Roundabout

The field study at the two-lane roundabout location focused on two crossing treatments. The treatments were (1) an RCW that was intended to reduce vehicle speeds and encourage yielding behavior, and (2) a PHB, also known as a HAWK signal. The PHB is intended to stop traffic at a red signal indication while minimizing vehicular delay because it is not a full signal, and to supply auditory information to the pedestrian via APS. All treatments were installed between the pretest and posttest. A more detailed description of the site and treatments is given in Chapter 3.

Crossing Performance Results

The evaluation of pedestrian crossing performance used the measures defined in Chapter 4: the availability of crossing opportunities in the form of yields and crossable gaps, the rate of utilization of these opportunities, the 85th percentile pedestrian delay, and the rate of O&M interventions. As discussed in that chapter, the analysis approach for two-lane crossing was revised slightly to reflect the fact that pedestrians are faced with two conflicting lanes. For ease of understanding, this chapter combines the three yield classifications (rolling, stopped, and forced) and only discusses differences where necessary. The reader is encouraged to refer to Appendix A of this report for a more detailed evaluation of the results.

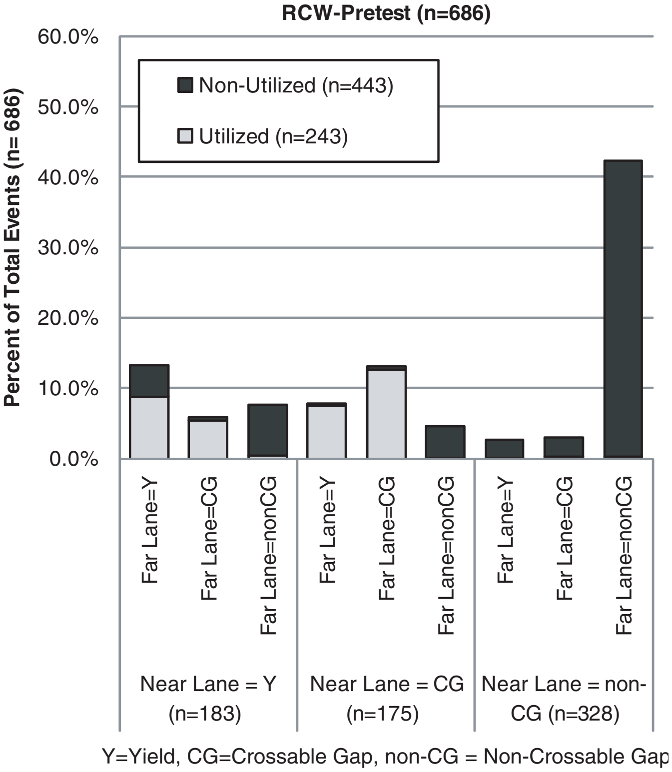
Concurrent with the two-lane roundabout data collection, participants also crossed at a nearby single-lane roundabout. The use of this comparison site was intended to allow for a direct comparison between the same participants' abilities to cross at a single-lane versus a two-lane roundabout. It further allowed the team to test for a learning effect since no treatments were installed at the single-lane roundabout. The results of the single-lane roundabout study were discussed above, and no such learning effect was evident. The starting order of participants was randomized as to which roundabout participants crossed at first. For crossings at the two-lane roundabout, the order of which of the two crosswalks was tested first was also randomized.

The pretest was completed in July 2008, and a total of 18 blind travelers participated in the study. The treatment was installed following the pretest, and 13 of the original 18 participants returned for the posttest in September 2008.

Raised Crosswalk

Figure 17 summarizes the encountered and utilized events at the RCW location during the pretest. As discussed, events are shown for the condensed matrix of near lane and far lane that combines the different yield types. The raw event data is contained in Appendix A.

The results in Figure 17 show that a total of 686 pedestrian–vehicle interaction events were observed in the pretest and that 443 of these (64.5%) were non-utilized events. This suggests pedestrian delay since blind pedestrians wait longer on average before utilizing an opportunity. The events are further divided into three vehicle states in the near lane in the categories of yield (183 events, 26.7%), crossable gap (175, 25.5%), and



This figure shows a bar chart of all observed pedestrian–vehicle events during the RCW pretest. The graph shows a total of nine event categories, representing all combinations of event outcomes yield, crossable gap, and non-crossable gap for two conflicting lanes (near lane and far lane).

Figure 17. RCW pretest event utilization.

non-crossable gap (328, 47.8%). For each near-lane category, the events are broken down by vehicle state in the far lane as well as by whether the particular event combination was utilized or not. Overall, the majority of events fell into the category of a non-crossable gap in both lanes, which can also be interpreted as drivers who did not yield to pedestrians. Expectedly, almost all of these events were not utilized by the pedestrians. The figure shows that some of the event combinations correspond to crossing opportunities (yield or crossable gap) in both lanes. The utilization statistics show that most of those opportunities involving at least one crossable gap were utilized, but that almost a third of the dual-yield events were not.

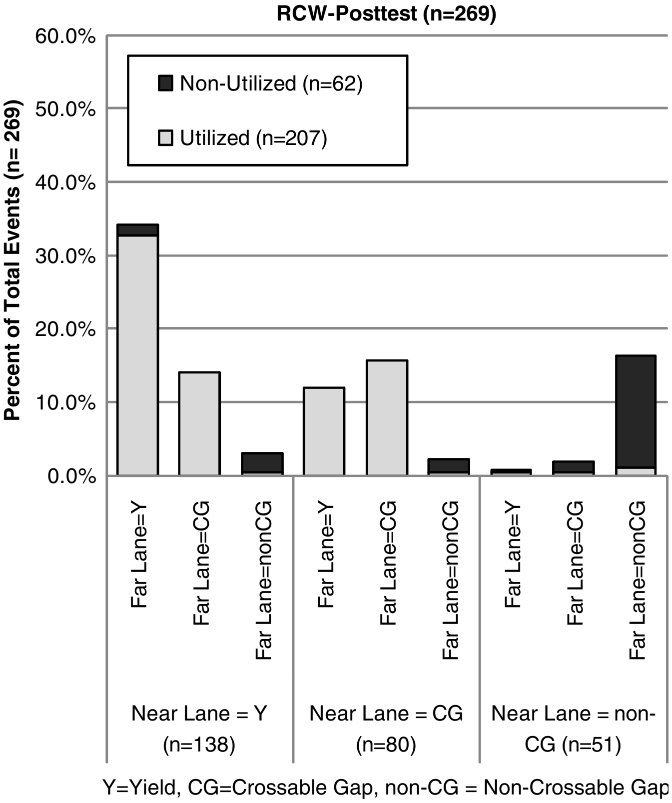
Special attention should be paid to the events with a near-lane yield and a far-lane non-crossable gap since these are related to the multiple-threat condition. This event combination represents 7.6% of all events, and 5.8% of these events actually were utilized by pedestrians (0.4% of all events). These potentially risky events need to be interpreted in addition to the O&M interventions that are discussed below. Overall, 1.3% of events were utilized events with a non-crossable gap in one or both lanes.

Figure 18 shows the corresponding event distribution for the RCW posttest. It shows a reduction in the number of events encountered by the pedestrian from 686 in the pretest to only 269 events. Accounting for the number of participants in the pretest (18) and posttest (12) studies, the resulting average number of events was reduced from 38 to only 22 events over 16 crossing attempts per participant. Consequently, participants in the posttest had much fewer non-utilized events (62) than in the pretest (443). This points to much improved decision-making efficiency as well as more courteous and/or compliant driver behavior.

A closer look at potentially risky events shows 3.0% of events that correspond to a potential multiple-threat situation with a near-lane yield and a far-lane non-crossable gap. Participants utilized 12.5% of these events, which represents 0.4% of all crossing events. Overall, 2.6% of events were utilized events with a non-crossable gap in one or both lanes. This suggests some potential risk at the crossing, in addition to the O&M interventions discussed below.

A comparison of Figure 17 and Figure 18 further shows that with the installation of the RCW, the relative percentage of yield events increased, and pedestrians also encountered more yields in both lanes. In return, the percentage of non-crossable gap opportunities decreased, suggesting that fewer drivers proceeded through the crosswalk without stopping. The utilization of dual crossing opportunities also increased, which is surprising since no audible message was associated with this particular treatment.

Following the discussion in Chapter 4, the nine event categories were converted to the probabilities of encountering and utilizing a crossing opportunity in both lanes, PA_Dual and PU_Dual, as well as in only one of the lanes PA_Half and PU_Half. By definition, the remaining events correspond to non-crossable events in both lanes (PA_No and associated utilization rate PU_No). Table 7 summarizes these statistics for the RCW analysis and also presents the associated delay and intervention statistics as defined previously.



This figure shows a bar chart of all observed pedestrian–vehicle events during the RCW posttest. The graph shows a total of nine event categories, representing all combinations of event outcomes yield, crossable gap, and non-crossable gap for two conflicting lanes (near lane and far lane).

Figure 18. RCW posttest event utilization.

Table 7 indicates that the availability of dual crossing opportunities increased significantly, from 56.0% to 76.9%, after RCW installation. The utilization of these events was already high during the pretest condition (88.3%) but increased further to 98.1%. This rate of utilization is rather extraordinary considering that the blind participants make crossing decisions about two conflicting lanes based on auditory information alone. Due to the reduction in non-crossable events that was discussed in relation to Figure 18, the occurrences of PA_Half and PA_No events both decreased. The utilization rates of these opportunities did not change significantly.

With more frequent and better utilized dual crossing opportunities, the delay experienced by participants decreased significantly, from 17.0 s to 8.0 s. The maximum average delay experienced by a single participant also decreased, from 84.9 s

Table 7. Crossing performance summary at RCW, pretest and posttest.

	RCW			
Performance Measure	**Pre**	**Post**	**Difference**	**p-value**
Dual Opportunities (PA_Dual)	56.0%	76.9%	20.9%	0.0003
Single Opportunities (PA_Half)	12.5%	7.8%	–4.7%	0.0842
None Opportunities (PA_No)	31.5%	15.3%	–16.2%	0.0016
Dual Utilization (PU_Dual)	88.3%	98.1%	9.8%	0.0062
Single Utilization (PU_Half)	12.9%	15.2%	2.3%	0.7980
None Utilization (PU_No)	2.0%	7.6%	5.7%	0.3257
Average Delay (s)	17.0	8.0	–9.0	0.0434
Delay>Min (s)	3.4	2.3	–1.1	0.2117
85th Percentile Delay (s)	29.8	12.9	–16.9	–
O&M Interventions	2.8%	0.0%	–2.8%	0.0230

to 18.2 s. The delay improvements are also mirrored in the Delay>Min and 85th percentile delay statistics.

From a crossing risk perspective, the installation of the RCW decreased the rate of O&M interventions from 2.8% to 0%. The 2.8% pretest interventions corresponds to a risk of 1 in 36 crossing attempts. The rate further represents eight individual observations distributed across six of the 18 participants. No interventions were observed for the 12 returning posttest participants. It is important to emphasize that four of these 12 did experience at least one intervention in the pretest condition. While the reduction of interventions to 0% is statistically significant, this number in all likelihood does not represent an absolute zero. It should therefore not be interpreted as the RCW resulting in zero risk to blind pedestrians. It is very unlikely that any treatment would result in zero risk to blind pedestrians or sighted pedestrians, as evident by pedestrian injuries and deaths at intersections across the country. The 0% intervention rate therefore should only be interpreted as the fact that no interventions were observed during the 16 crossing attempts by each of the 13 participants during the posttest.

Overall, the installation of the RCW resulted in drastic improvements in crossing performance at this location, both in terms of delay and safety. It is emphasized here that these findings are only representative of this one crossing location. However, the results do seem to suggest that the RCW treatment shows a lot of promise at two-lane roundabout approaches. Prior research (Geruschat and Hassan 2005) has linked lower speeds to an increased likelihood of yielding, which likely explains the effect observed here.

More surprising is that while the RCW seemingly improved the utilization of crossing opportunities, no treatment was installed that was intended to provide more information to blind pedestrians. Two possible explanations are offered: (1) The RCW gave pedestrians increased confidence in utilizing crossing opportunities. It therefore may not have improved the ability of pedestrians to detect opportunities (yields), but rather increased their willingness to step in front of yielding vehicles. (2) Driver stopping behavior may have been altered with the RCW installation. In the pretest condition, many drivers were observed to slowly coast to a stop and to approach the crosswalk cautiously. This form of a rolling yield is difficult to distinguish auditorily from background noise at the roundabout. In the posttest condition, driver yielding behavior seemed to be more rapid. In other words, cars quickly decelerated to a stop in proximity of the crosswalk, much like they would stop at a signalized intersection or a stop sign. This modified deceleration rate seemed to be more discernable auditorily, which presumably aids utilization.

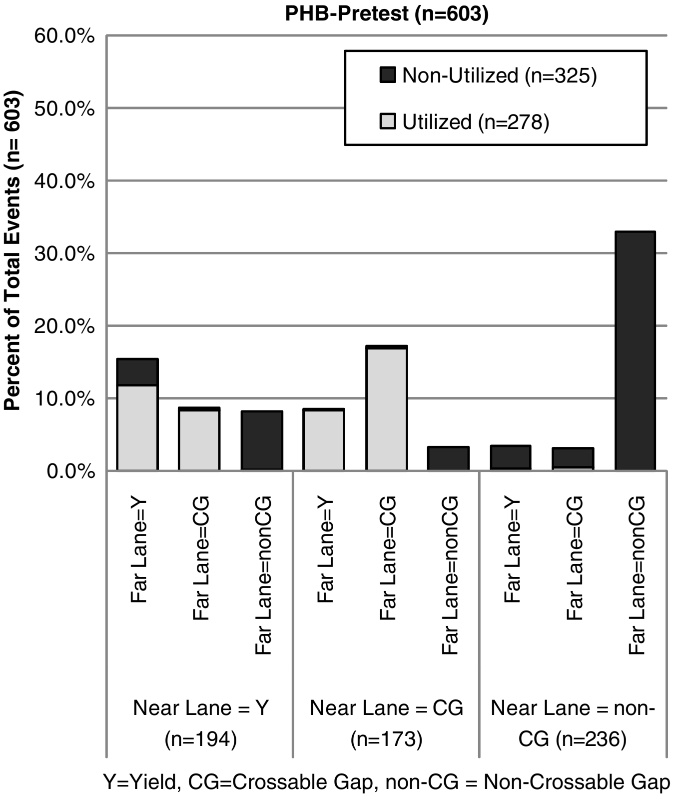
Pedestrian Hybrid Beacon

Figure 19 summarizes the encountered and utilized events for the PHB location in the pretest. As discussed previously, results are shown for the condensed matrix of near-lane and far-lane events. The raw event data is contained in Appendix A.

Figure 19 shows similar trends at this crossing to those that were observed at the RCW pretest. More than half of the events (325 out of 603) represent non-utilized opportunities and indicate delay. Similar to the other studied crosswalk, over 30% of events correspond to non-crossable gaps in one or more lanes, signifying drivers that did not yield to the pedestrians. Among those events that do represent crossing opportunities in both lanes, the rate of utilization is again lowest for dual-yield events.

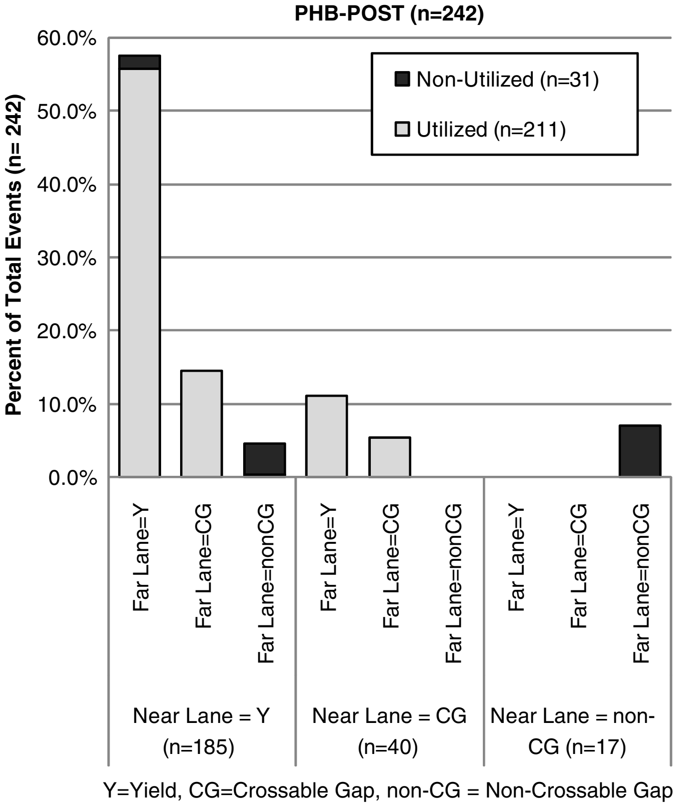
The figure further shows that 8.1% of events are associated with a potential multiple-threat situation with a near-lane yield and a far-lane non-crossable gap. Participants utilized only 2.0% of those events at this crossing, which represents 0.2% of all crossing events. Overall, 1.0% of events were utilized events with a non-crossable gap in one or both lanes.

Similar to the RCW, the results in Figure 20 show a reduction in events encountered by the pedestrian, from 603 to 242



This figure shows a bar chart of all observed pedestrian–vehicle events during the PHB pretest. The graph shows a total of nine event categories, representing all combinations of event outcomes yield, crossable gap, and non-crossable gap for two conflicting lanes (near lane and far lane).

Figure 19. PHB pretest event utilization.



This figure shows a bar chart of all observed pedestrian–vehicle events during the PHB posttest. The graph shows a total of nine event categories, representing all combinations of event outcomes yield, crossable gap, and non-crossable gap for two conflicting lanes (near lane and far lane).

Figure 20. PHB posttest event utilization.

events. Again, this reduction is primarily attributable to the greatly reduced number of non-utilized events, from 325 in the pretest to only 31 in the posttest, signifying improved decision-making efficiency and more courteous (signal compliant) driver behavior with installation of the PHB. Figure 20 further shows that with the installation of the PHB, most encountered events fell into the yield category, which corresponds to vehicles stopping at the red signal indication. Similar to the RCW, very few non-crossable gap events were encountered in the posttest condition.

The figure also shows that 4.5% of posttest events are associated with a potential multiple-threat situation and that participants utilized 9.1% of these events (0.4% of all crossing events). Overall, only 0.4% of events were utilized events that were associated with a non-crossable gap in one or both lanes.

Following the discussion in Chapter 4, the nine event categories may be converted to the probabilities of encountering and utilizing a crossing opportunity in both lanes, PA_Dual and PU_Dual, as well as in only one of the lanes PA_Half and PU_Half. Table 8 summarizes these statistics for the PHB analysis and also presents the associated delay and intervention statistics as defined previously.

Table 8 shows an increased probability of encountering dual crossing opportunities, from 55.5% to 89.3%. The rate of utilization of these events was high in the pretest condition (91.6%) and was increased further in the posttest (98.3%). Similar to the RCW, the rate of PA_Half and PA_No opportunities decreased, which is explained by fewer non-crossable gap events and generally less non-utilized events (see Figure 20).

Accordingly, the average pedestrian delay statistics improved significantly with PHB installation, from 16.0 to 5.8 s. This trend is mirrored in the Delay>Min and 85th percentile delay times. The single highest average delay was 46.5 s in the pretest and 14.6 s in the posttest.

The PHB also improved pedestrian safety performance and reduced interventions from 2.4% to 0%. In the pretest, seven interventions were distributed among six of the 18 participants. Five of those six participants returned for the posttest, and no interventions were observed for them or the other seven posttest participants. A 2.4% intervention rate corresponds to a risk of 1 in 42 crossing attempts. Similar to the RCW, it is important to emphasize that while the reduction of interventions to 0% is statistically significant, this number in all likelihood does not represent an absolute zero. It should therefore

Table 8. Crossing performance summary at PHB, pretest and posttest.

	PHB			
Performance Measure	**Pre**	**Post**	**Difference**	**p-value**
Dual Opportunities (PA_Dual)	55.5%	89.3%	33.8%	<.0001
Single Opportunities (PA_Half)	15.0%	4.1%	–10.9%	0.0001
None Opportunities (PA_No)	29.5%	6.6%	–23.0%	<.0001
Dual Utilization (PU_Dual)	91.6%	98.3%	6.7%	0.0062
Single Utilization (PU_Half)	8.8%	8.3%	–0.5%	0.9468
None Utilization (PU_No)	0.0%	0.0%	0.0%	–
Average Delay (s)	16.0	5.8	–10.2	0.0007
Delay>Min (s)	3.2	1.4	–1.8	0.0044
85th Percentile Delay (s)	29.5	7.7	–21.8	0.0001
O&M Interventions	2.4%	0.0%	–2.4%	0.0112

not be interpreted as the PHB resulting in zero risk to blind pedestrians. It is very unlikely that any treatment would result in zero risk to blind pedestrians or sighted pedestrians, as evident by pedestrian injuries and deaths at intersections across the country. The 0% intervention rate therefore should only be interpreted as the fact that no interventions were observed during the 16 crossing attempts by each of the 13 participants during the posttest.

Overall, the installation of the PHB resulted in significant improvements in crossing performance from a delay and safety perspective. In the interpretation of the delay times, it needs to be highlighted that the study design used in the PHB study assumed that pedestrians arrived at the crossing after the minimum green time had elapsed. Effectively, this design minimized the potential delay encountered by pedestrians. At a phase cycle length of 38 s, this assumption is valid for pedestrian volumes of less than 90 per hour (which would result in pedestrian headways of 40 s assuming uniform arrivals). For heavier pedestrian flows, this assumption does not hold because additional pedestrians are increasingly likely to arrive just after the "Walk" phase has elapsed and higher delays are anticipated. However, as demonstrated in a simulation-based sensitivity analysis of roundabout PHB installations (Schroeder et al. 2008), additional pedestrians will also be more likely to join existing signal calls. The pedestrian delay therefore plateaus with increasing pedestrian demands, where the magnitude of this terminal delay is a function of the signal phasing.

Participant Feedback

Following each the pretest and posttest two-lane roundabout studies, participants were asked a series of questions about their perception of the crossing and the level of comfort in their crossing decisions. The blank survey forms are provided in Appendix G.

The participant feedback at the two-lane roundabout presents a somewhat different picture than the feedback at the single-lane roundabouts or the CTL. The average of the responses on the confidence question ("How would you rate your confidence in your ability to cross here safely on a scale of 1–5, with 1 being not at all and 5 very confident?") was 4.0 in the pretest, 4.83 at the PHB installation posttest, and 4.58 in the RCW crossing posttest. On the question, "Would you use these crossings if they were on the most direct route home from work?" in the pretest, 15 participants said yes, and 1 said "no, would find another way." In the posttest, with the PHB, 12 said yes and no one said no, and with the RCW, 11 said yes and one said no. While the numbers were positive in the pretest and posttest conditions, the comments that were noted along with the responses changed considerably. In posttest debriefing, comments at the PHB were generally more enthusiastic, with additions like "definitely!" or "would go out of my way to use them."

A couple of questions were added for the Golden debriefing that provide a little more insight into the participants' thinking. Participants were asked if they considered the crossings more risky, less risky, or of about the same risk as an intersection with a signal and four lanes of traffic. Table 9 shows the frequency of responses and percentages in parentheses.

In the pretest, 17% considered the two-lane roundabout less risky, and about 40% each thought it was the same or more risky than a signalized intersection. In the posttest, at the PHB, 54% considered it less risky and 31% about the same risk. Only one person thought it was more risky, compared to seven in the pretest. At the RCW, 23% considered it less risky, 62% about the same risk, and again only one person (8%) more risky than a signal. Presumably, this suggested greater confidence and comfort in participants' perception of the PHB relative to the RCW. Both treatments showed perceived benefits over the base two-lane roundabout case, as well as the (hypothetical) signalized intersection.

Table 9. Participant survey comparison of two-lane roundabout treatments.

	Less Risky	About the Same Risk	More Risky	Not Answered
Pretest (n=18)	3 (17%)	7 (39%)	7 (39%)	1 (6%)
PHB (n=13)	7 (54%)	4 (31%)	1 (8%)	1 (8%)
RCW (n=13)	3 (23%)	8 (62%)	1 (8%)	1 (8%)

As discussed in the previous sections on participant feedback, the participants' suggestions of intersection modifications after their crossings in the pretest may provide additional information about their concerns. Some suggested signals, even though some of those same individuals said that they were not fans of audible signals, and suggested that it would be good if the signal could be used optionally. One suggested a light that signaled to motorists that pedestrians were waiting to cross. Some suggested that detectable warnings needed to be present on both crosswalks (for some reason detectable warnings were only installed on the north crosswalk during pretest). One suggested some way to know that it was a roundabout when approaching as a pedestrian, and another suggested moving the exit crosswalks further from the roundabout circulatory roadway.

In the posttest, participants commented about the uneven surface of the raised crosswalk and the need to have a smoother transition. Several made positive comments about the signal and push-button locator tone; one said: "if they're going to use locator tones, those were pretty good." At posttest, participants seemed generally happy with the modifications, particularly the pedestrian hybrid beacon. Several stated that the raised crosswalk didn't make a difference, while others felt it made a big difference in drivers' willingness to yield.

Participants in the posttest were also asked several questions specific to the PHB, the push-button locator tone, and the audible message (see Table 10). For the questions in the table, participants were asked to rate the extent of their agreement, with 1 being strongly disagree and 5 strongly agree.

The responses suggest some hesitation in the expected use and effectiveness of the PHB. While most said they would use the APS device, only a few said they would wait for the audible "Walk" message (and thereby the "Walk" signal phase). Most respondents acknowledged the benefit of the push-button locator tone to identify the crossing locations, but responses on initial alignment and maintaining alignment during crossing were mixed. It needs to be acknowledged here that the locator tones were generally too quiet in this installation to be audible across the width of the street. Therefore, participants generally couldn't hear the far-side message or locator tone until a little past the middle of the crossing. The far-side APS did seem to help people know when they were about to reach the end of the crosswalk. Some participants negatively commented on the fact that the push buttons on the island were installed on top of a wall used to contain landscaping, which they didn't expect. This part of the installation clearly wasn't ideal and was partly related to the temporary nature of this PHB installation.

Compliance with Signal Indications

Pedestrian Compliance

The analysis of pedestrian crossing performance does not consider an important aspect of the behavior at the PHB: the signal phase during which pedestrians chose to cross. The analysis results remain valid since they describe pedestrian actions in terms of actual driver behavior. For example, most drivers are expected to stop before the "Walk" phase comes on. Similarly, a "Walk" indication is no guarantee of perfect driver compliance and is associated with a risk of red-light running events. Consequently, the analysis above initially ignored the signal phase. This also ensures that the results are directly com-

Table 10. Participant survey response to PHB installation.

Rating Questions	Average of Responses (N=10) 1=strongly disagree, 5=strongly agree
If there were signals like these, I'd push the button each time I wanted to cross	3.7
If there were signals like these, I would always wait to cross until I hear "walk sign is on."	2.0
These signals helped me know I was coming to the crosswalk.	4.2
These signals helped me align to cross.	2.4
These signals helped me go straight across the crosswalk.	2.4
These signals helped me know I was approaching the end of the crosswalk	3.4

parable to the pretest condition as well as crossing performance at the RCW crossing.

Nonetheless, the installation of the PHB is associated with some legal implications for when pedestrians should cross. At the PHB, the vehicle signal display rests in a "Dark" mode pending a pedestrian's pressing of the APS push button. While the language in the MUTCD (FHWA 2009) allows for a PHB to rest in "Dark" for the pedestrian mode, this was not the case at the tested installation. The pedestrian display for the signal rested in "Don't Walk," as a conventional signal would. Consequently, pedestrians were expected to push the button and wait to cross until the onset of the "Walk" phase. In this project, participants were informed of the phase sequence and intended behavior. However, they were always instructed to "cross when they are ready" and to "rely on their own judgment" when making crossing decisions. Participants were not given any specific information regarding the legal issue of beginning crossing during "Walk" at pedestrian signals. In other words, pedestrians were not told that they **had** to cross in the "Walk" phase.

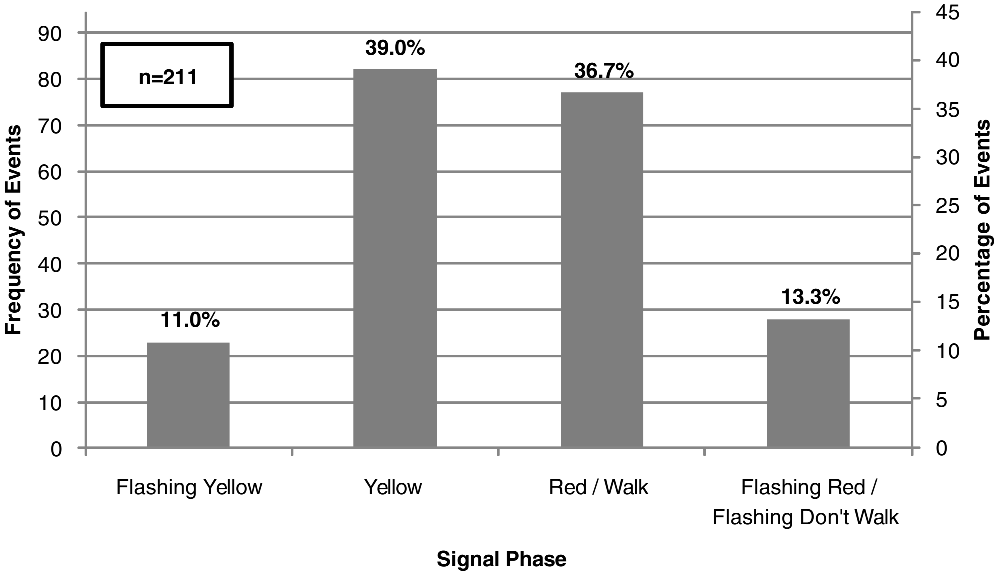
With the PHB, pedestrians encountered a signal indicating that the signal phase is either "Walk" (W), "Flashing Don't Walk" (FDW), or "Don't Walk" (DW). Blind pedestrians heard a push-button locator tone during the DW and FDW phases and a speech message during the W phase. Figure 21 shows the frequency of crossing initiation for the (blind) pedestrian relative to PHB signal phases. More details on the PHB phase sequence and timing parameters were given in Chapter 3.

The results show that only 36.7% of pedestrians crossed in the intended "Walk" phase and that many (39.0%) actually initiated the crossing just before the "Walk" phase (and the APS alert) in the vehicular solid yellow. In other words, they began to cross following pressing the call button but prior to the audible message. Further, 11% crossed even earlier, during the vehicle "Flashing Yellow" phase, and 13.3% didn't cross until the flashing "Don't Walk" phase. Overall, only three times did pedestrians not cross in the first crossing phase and have to reactivate the signal. From anecdotal observation, participants appeared to cross whenever they first heard cars stop. The actual pedestrian signal display at that time seemed to be less important to the participants. As discussed above, observations further suggested that driver deceleration behavior was more rapid and the stop location was closer to the crosswalk, which seemed to make these yields more distinguishable for the blind participants. It is re-emphasized here that participants were not instructed that they had to cross during the "Walk" phase.

These findings suggest that the study participants rely heavily on their own personal judgment, even with the signal beacon in place. Pedestrians tended not to cross in "Walk" if they were unsure about whether vehicles had in fact stopped. Even when the audible message confirmed to the blind pedestrian that a "Red" signal indication was being presented to an approaching driver, some would still not cross until they were confident that it was safe to do so. Similarly, they would readily cross before the "Walk" phase if they perceived a crossing opportunity.

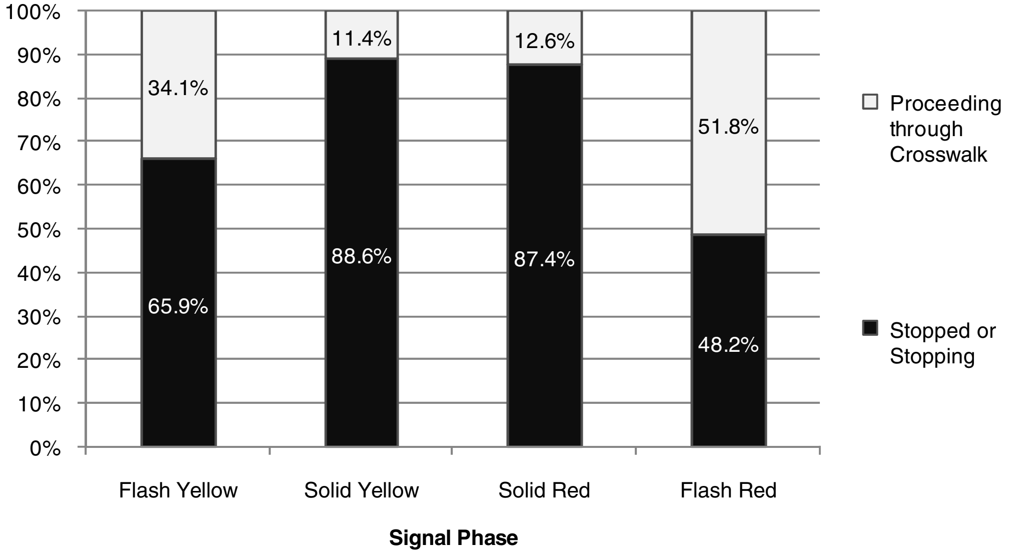
Driver Compliance

In the evaluation of the PHB, an important question of interest to traffic engineers is the behavior of drivers relative to the signal phases. In particular, the PHB is intended to reduce



This figure shows a bar chart of pedestrian crossing behavior in regard to the four PHB signal displays: "Flashing Yellow/Don't Walk," "Yellow/Don't Walk," "Red/Walk," and "Flashing Red/Flashing Don't Walk." The results are discussed in the text.

Figure 21. Blind pedestrian crossings at PHB by signal phase (% of all crossings).



This figure shows a bar chart of driver behavior in regard to the four PHB signal displays: "Flashing Yellow/Don't Walk,' "Yellow/Don't Walk," "Red/Walk," and "Flashing Red/Flashing Don't Walk." The results are discussed in the text.

Figure 22. Evaluation of driver behavior at PHB.

vehicular delay by allowing drivers to proceed during the "Flashing Red" phase. The following analysis is intended to capture driver understanding of and compliance with the signal indication.

Driver understanding of and compliance with the PHB can be evaluated by relating the driver stopping behavior to the indicated signal phase. Figure 22 plots two categories of driver behavior for each signal phase: (1) vehicles stopped or stopping, and (2) vehicles proceeding through the crosswalk. The figure shows four signal phases that correspond to the PHB phasing sequence for vehicles: "Flashing Yellow," "Solid Yellow," "Solid Red," and "Flashing Red."

The figure shows that 34.1% of drivers proceeded through the crosswalk in "Flashing Yellow," which is permitted behavior. As the signal changed to "Solid Yellow," 11.4% of drivers proceeded through the crosswalk, which is allowable if the vehicles were too close to the crosswalk to come to a stop. However, even during the "Solid Red," 12.6% of observed vehicles proceeded through the crosswalk. This statistic is a concern, since drivers are legally required to stop for the red signal indication and because pedestrians expect a crossing opportunity. Driver behavior during "Flashing Red" shows that almost half of the drivers (48.2%) remained stopped, suggesting some inefficiency in driver behavior in response to the PHB.

These findings raise some concerns that the PHB traffic control device may not have been properly understood by drivers or that the PHB display was ignored. An education campaign by the city of Golden, using web and news media outlets, informed citizens of the PHB installation at the test roundabout and discussed appropriate behavior. However, it is unclear how frequently the device was actually used in the 6-week driver adaptation period prior to the posttest. Further, frequent tourist and non-commuter traffic in the area may have contributed to driver confusion. Given the apparent lack of understanding of the PHB, it seems that the flashing red indication of the traffic control was not intuitive to drivers.

Impact on Vehicular Traffic

Raised Crosswalk

A pretest and posttest speed study was performed at the RCW installation to estimate the impact of the treatment installation on free-flow vehicle speeds. All speeds were collected from video observations using known reference distances from roadside markers. The speeds correspond to the average speed just upstream of the crosswalk, measured over a distance of approximately 100 ft at exit and 160 ft at the entry leg. The study included only free-flowing vehicles that passed through the crosswalk in the absence of pedestrians. A sample size of approximately 100 vehicles was collected for the entry and exit leg of the roundabout in both pretest and posttest conditions. The total dataset of 405 observations was collected for different times of day and on different days of the week.

The results show an average entering speed approaching the crosswalk of 25.3 mph, which was significantly reduced to 20.5 mph with the installation of the raised crosswalk ($p < 0.0001$). While this speed reduction is as anticipated, the posttest speeds were still relatively high given the RCW treatment. This is attributed to the relatively low vertical height and gentle slope transition that was used in the RCW design. The design therefore results in a relatively low impact on vehicle speeds in the absence of pedestrian and vehicle platoons, while still showing beneficial impacts on pedestrian crossing performance as discussed above.

At the exit leg, the average pretest speed of 17.7 mph was reduced to 16.1 mph ($p < 0.0001$). While statistically significant, the practical implication of this speed reduction is marginal in terms of vehicle delay. But again, as the analysis above showed, the RCW had a very positive impact on pedestrian crossing performance, despite the relatively low speed impact.

Pedestrian Hybrid Beacon

A special queuing study was performed at the PHB installation to address concerns that the signal would cause extensive queuing and that those queues could spill back into the circulating lane. The analysis measured the maximum queue length for each pedestrian crossing in all pretest and posttest trials. The maximum queue was defined as the longest pedestrian-induced queue length measured in vehicles. Queues were measured relative to the crosswalk and therefore do not include additional vehicles that were waiting to enter the roundabout downstream of the crosswalk (at the entry). Vehicle queues were combined for both lanes since no significant difference was observed between queues in the inside and outside lanes.

The results showed that the average maximum queue length increased from 2.3 to 5.0 vehicles at the entry and from 1.5 to 3.9 vehicles at the exit over both approach lanes. The increases in average maximum queues are significant at $p < 0.0001$. With available queue storage of two vehicles (one per lane) at the exit leg, it is evident that the maximum queue sometimes spilled back into the circulating lane. With the installation of the PHB, that proportion of maximum queues greater than two vehicles increased from 29.8% to 69.2%. However, the average queue is expected to be much lower, so that the overall effect of the PHB installation on vehicle queues is considered to be marginal. In fact, a determined yielder may be stopped for 10 or more seconds waiting for the pedestrian to cross and is likely to cause similar if not more delay to a driver waiting at the PHB, as evident by some long queues observed in the pretest. More detail on the queuing analysis is given in Appendix A.

Summary of Results

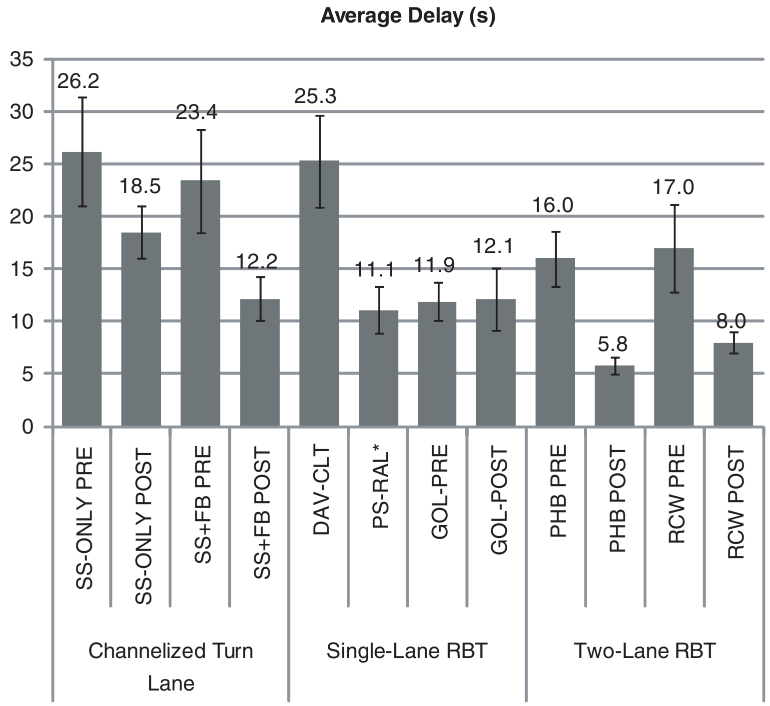
This chapter presented findings from 12 rounds of field studies performed at a total of seven pedestrian crossings: two channelized right turn lanes, three single-lane roundabout crossings, and two two-lane roundabout crossings. While no treatments were tested at the single-lane roundabout locations, the remaining crossings and studies included pretest and posttest comparisons of the effectiveness of different treatments in improving accessibility of these locations. All 12 studies were performed using the same experimental protocol. The study for one of the single-lane roundabouts (PS-RAL) was performed as part of an earlier research project (NIH 2010). The remaining data collection occurred under the auspices of NCHRP Project 3-78A. For these 11 rounds of testing, the same O&M specialist was used to establish consistency and uniformity in the experimental design. This point is especially important in light of the rate of O&M interventions, an important safety measure used in the analysis.

The analysis framework was discussed in detail in Chapter 4 and uses a four-pronged approach for assessing the accessibility of a crossing through (1) the availability of crossing opportunities, (2) the rate of utilization of these opportunities, (3) the delay experienced by the pedestrian, and (4) the level of risk associated with the crossing. The first two measures are largely intended to find an explanation for the latter two. This section summarizes some of the delay and risk measures to allow a comparison across the different test locations.

Figure 23 summarizes the average delay across all participants for the 12 locations. The graph further contains error bars at 1 standard error of the estimate of the mean. The standard error is calculated by dividing the standard deviation of the estimate by the square root of the sample size (number of participants). The summary chart shows highest delays observed at the two CTL locations in the pretest treatment condition as well as for the DAV-CLT single-lane roundabout. Interestingly, these three data points represent very different traffic conditions, but were all located in Charlotte. At DAV-CLT, volumes were low and participants were delayed despite ample gap crossing opportunities as many waited for all-quiet periods. At the two CTL crossings, traffic volumes were much higher, and the delay was exacerbated by a very high level of ambient noise from the main intersection. All three of these locations were characterized by a low propensity of drivers to yield, which may be characteristic of the local driving culture or may be coincidence. With treatment installation, the average delay at CTL crossings was reduced. No treatment was tested at the single-lane roundabout.

Of the remaining sites, the two-lane roundabout crossings exhibited the highest average delay and the highest variability across participants. The two-lane roundabout delay was reduced significantly with installation of either crossing treatment (RCW and PHB) to levels that were below the remaining single-lane roundabout delays. It is important to emphasize that the studies at the two-lane and single-lane roundabouts in Golden were performed concurrently with the same participants. Consequently, these sites can be directly compared. The comparison shows that delays were higher at the two-lane roundabout and there was greater variability across participants. The assessment of the PHB and RCW treatments further highlights that pedestrian delay and risk were effectively improved over the base condition of the single-lane roundabout comparison site.

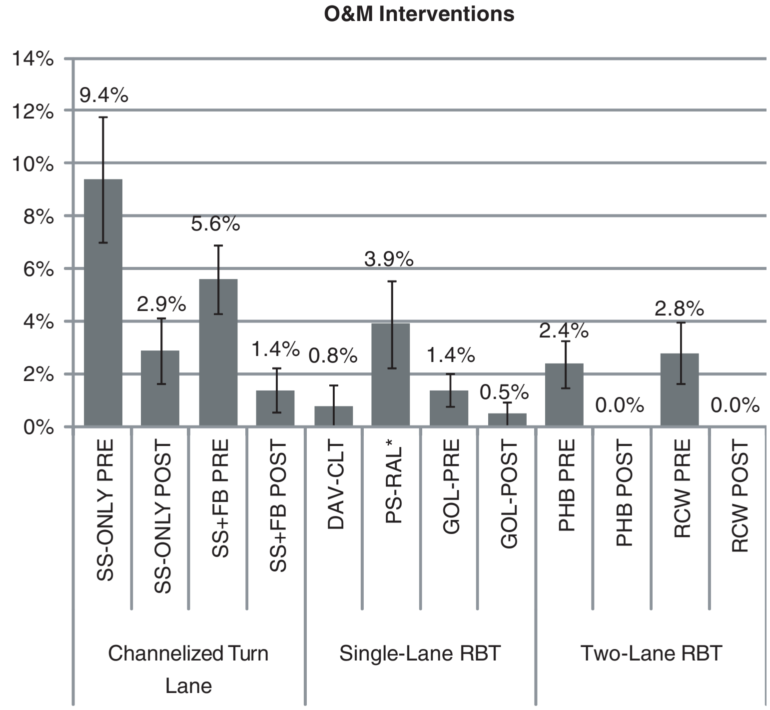
Figure 24 shows the comparative results of O&M interventions across the 12 test conditions. Again the figure shows the



This figure shows a bar chart of the summary of the delay results at all test sites and all study conditions. The graph shows the average pedestrian delay observed for each of 12 studies as well as the standard error of that estimate. The results are discussed in the text.

Error bars shown at 1 standard error
*Data collection performed in prior research

Figure 23. Summary of 85th percentile delay for all sites.



This figure shows a bar chart of the summary of the O&M intervention results at all test sites and all study conditions. The graph shows the average pedestrian delay observed for each of 12 studies as well as the standard error of that estimate. The results are discussed in the text.

Error bars shown at one standard error
*Data collection performed in prior research

Figure 24. Summary of O&M interventions for all sites.

average observed over all participants and the standard error of the estimate.

The intervention comparison shows very high risk at the CTL crossings in the pretest condition along with a very high variability across participants. Intervention rates at the CTL locations were reduced with treatment installation, but some interventions remained even in the posttest condition. For the roundabouts, the highest intervention rate was observed at PS-RAL, although this study was not performed as part of NCHRP Project 3-78A. With the use of different O&M instructors there is the potential that individual differences may be a contributing factor to the difference in intervention rates. Since the remaining 11 data points all involved the same O&M specialist, greater comfort exists that the results are comparable. Consequently, the two-lane roundabout pretest conditions exhibited the greatest level of risk among the roundabouts and the largest variability across participants. With treatment installation, no interventions were observed at these locations.

CHAPTER 6

Study Extensions

The objective of this chapter is to extend the analysis results from Chapter 5 to a broader and more applied context. Because of limited resources, only a small number of sites were represented in the field experiment. But clearly, the crossing challenges for pedestrians who are blind extend to other geometries and traffic patterns. This chapter attempts to provide this type of extension in two ways:

1. The development of *pedestrian delay models* that allow the analyst to predict the expected pedestrian delay at a crossing location based on traffic patterns and behavioral attributes of drivers and pedestrians.
2. A discussion on how to apply t*raffic simulation models* to extrapolate the effects of other treatments to other sites, including treatment combinations not captured in the experimental field trials.

This chapter presents the pedestrian delay models and discussion of traffic simulation models consecutively. The reader should be aware that with limited field data, both areas of extension are to be treated with care. The analyst should always apply expert judgment in any treatment installation and evaluation. Other national resources provide additional information on the effectiveness of different treatments (Fitzpatrick et al. 2006) and on case studies describing lessons learned from their installation (Zegeer et al. 2002). The approach for developing pedestrian delay models has been separately published in Schroeder and Rouphail (2010).

The principal focus of the two extensions is on pedestrian delay, not risk. This is a clear limitation that needs to be recognized early on. The NCHRP Project 3-78A team attempted to follow similar approaches to predict the safety performance of a pedestrian crossing using regression and simulation techniques. The regression-based attempt was not successful due to the rare occurrence of O&M interventions. In order to develop a risk prediction model from field data, a different dependent variable would be needed that is readily observable for every participant. The section on simulation models does describe an approach for using simulation to extract surrogate safety measures and a way to model the unique aspects of how blind pedestrians interact with vehicles. However, the best measure of safety remains the field-measured rate of O&M interventions presented in Chapter 5. Chapter 7 discusses in more detail the interpretation of the results and the implications for roundabout and CTL facility design.

Delay Estimation

Introduction

The analysis results in Chapter 5 confirmed the hypothesis that pedestrian–vehicle interaction at unsignalized roundabout and channelized turn lane crosswalks is characterized by a mix of pedestrians' (crossable) gap acceptance and driver yielding behavior. Both represent crossing opportunities since pedestrians cross in between two vehicles (gap) or in front of a yielding vehicle. The crosswalks are typically marked with a zebra pattern or another form of marking (Rodegerdts et al. 2007) and feature a pedestrian splitter island to separate the interaction between different directions of moving traffic. State motor vehicle codes commonly give pedestrians the right-of-way within the crosswalk, suggesting that roundabouts and CTLs should be very accessible to pedestrians. But yielding laws can be misinterpreted, and the actual yielding behavior varies over a range of observed values at different sites and geometries (Fitzpatrick et al. 2006). Consequently, pedestrians are expected to experience some delay when attempting to cross at these locations.

The interaction of the two modes therefore needs to be represented by a "mixed-priority delay model" (Schroeder and Rouphail 2010) that acknowledges the mix of yielding and gap acceptance. The 2000 *Highway Capacity Manual* (TRB 2000), the guidebook for traffic operational analysis methodologies for the United States and many other countries, currently offers no delay methodology for a mixed-priority crossing situation, where drivers sometimes yield to create crossing opportunities but where pedestrians sometimes have to rely on their judgment of gaps in traffic to cross the street. The HCM gap-acceptance–based methods are limited to cases where pedestrians have full priority (100% of traffic yields) or where drivers have priority (no yields) and pedestrians are limited to crossings in gaps between moving vehicles only. An updated pedestrian delay model that allows for a reduction of pedestrian delay due to driver yielding is being considered for the 2010 release of the HCM. However, the proposed theoretical model is not calibrated from field data and does not distinguish between different subpopulations of pedestrians.

With currently available HCM pedestrian delay models, it is therefore not possible to represent the mixed-priority interaction that was observed at the studied CTL and roundabout crosswalks. Furthermore, the HCM approach does not adequately capture the observed utilization rates of crossing opportunities. For example, a gap-acceptance–based delay model assumes that pedestrians utilize every crossable gap, which was found not to be the case for blind pedestrians. This section develops mixed-priority pedestrian delay models that capture the mix of yields and crossable gaps encountered and acknowledge the different utilization rates observed for different sites and by different participants. A more detailed description of the delay model development is given in Appendix K.

Approach

The mixed-priority delay models are developed on the premise of the accessibility framework presented in Chapter 4. It is hypothesized that the rates of occurrence and utilization of yield and gap crossing opportunities are correlated to pedestrian delay. Using a multi-linear regression approach, the dependent variable, delay, can therefore be described as a function of the four probability parameters P(Y_ENC), P(CG_ENC), P(GO|Y), and P(GO|CG). Chapter 5 contains the raw data used to generate the results for each participant at each of the test sites, along with the average delay experienced by that participant.

In the field experiments, blind participants crossed independently at three different single-lane roundabouts, two crosswalks at a two-lane roundabout, and two crosswalks at an intersection with CTLs. In each study, each participant crossed multiple times. Each trial consisted of four lane crossings at roundabouts (for example, entry–exit–exit–entry) and two lane crossings for the CTL (curb–island and island–curb). At each site, every pedestrian completed multiple trials to obtain an estimate of average crossing performance. These crossing-specific averages were used in the mixed-priority delay model development.

Variable Definitions

Many of the variables used in the delay model development are similar to the ones included in the Chapter 5 analysis and have been defined in Chapter 4. Initial independent variables included P(Y_ENC), P(CG_ENC), P(GO|Y), and P(GO|CG). The dependent variable for the models is the average pedestrian delay from the time a trial started until a crossing was initiated.

For model development, some additional explanatory variables are defined. They are obtained by manipulating the original behavioral probabilities.

- **P(Y_and_GO):** The probability of crossing in a yield, defined as the probability of encountering a yield multiplied by the probability of utilizing a yield:
  - P(Y_and_GO) = P(Y_ENC) ∗ P(GO|Y).
- **P(CG_and_GO):** The probability of crossing in a crossable gap, defined as the probability of encountering a CG multiplied by the probability of utilizing a CG:
  - P(CG_and_GO) = P(CG_ENC) ∗ P(GO|CG).
- **P(Cross):** The probability of crossing, defined as the sum of the probabilities of crossing in a yield or crossing in a crossable gap.
  - P(Cross) = P(Y_and_GO) + P(CG_and_GO)

Different delay models were developed for the three types of sites: CTL, single-lane roundabout, and two-lane roundabout. Some additional binary variables were defined to distinguish between different sites, different crossings, different treatments, and pretest and posttest treatment periods.

The model development uses a multi-linear regression approach to predict the dependent variable, delay, as a function of various independent variables. All variables are given on a per-leg basis at the roundabout, and as a result, the total delay for a two-stage crossing at a roundabout is twice the estimate (assuming the probabilities are the same). CTL crossings are single-stage only. A histogram of the distribution of the delay variable showed significant skew to the left, suggesting a log-normal distribution. Consequently, all predictive probability variables were transformed by applying the natural logarithm of the variable. All regression is performed in SAS statistical analysis software (SAS 1999) using PROC GLM, a procedure to perform multi-linear regression.

Results

This section presents an overview of the resulting delay models. Results are presented consecutively for the CTL, single-lane roundabout, and two-lane roundabout models, respectively. The results include the recommended delay equation for the three classes of crossings as well as a graphical representation of the models. The graphs are only shown for illustrative purposes since only one or two dimensions can be shown at one time. For example, delay might be a function of four parameters [(P(Y_ENC), P(GO|Y), P(CG_ENC), and P(GO|CG)], but assumptions need to be made on some variables in order to produce a visual plot of others. In application of the models, analysts should always use the equation form of the model. For additional details on model development, the reader is directed to Appendix K.

Channelized Turn Lane Delay Model

A total of 30 participants (16 pretest and 14 posttest) were included in the analysis. Each observation represents the average of 12 to 20 trials (6 to 10 round trips with two crossing trials each). With the distinction of the two studied crosswalks as well as pretest and posttest observations, the dataset thus contains 60 observations. One observation had to be excluded from the dataset since the participant did not encounter any yielding from drivers. As a result the final dataset contained 59 observations.

Various model forms were tested and are discussed in detail in Appendix K. Model selection was guided by statistical significance (overall model significance, parameter significance, and adjusted R-square value), as well as practical significance (model simplicity, reasonableness of results, fit with field-observed data). Equation 1 shows the suggested pedestrian delay model.

Equation 1. Suggested pedestrian delay model for CTL.

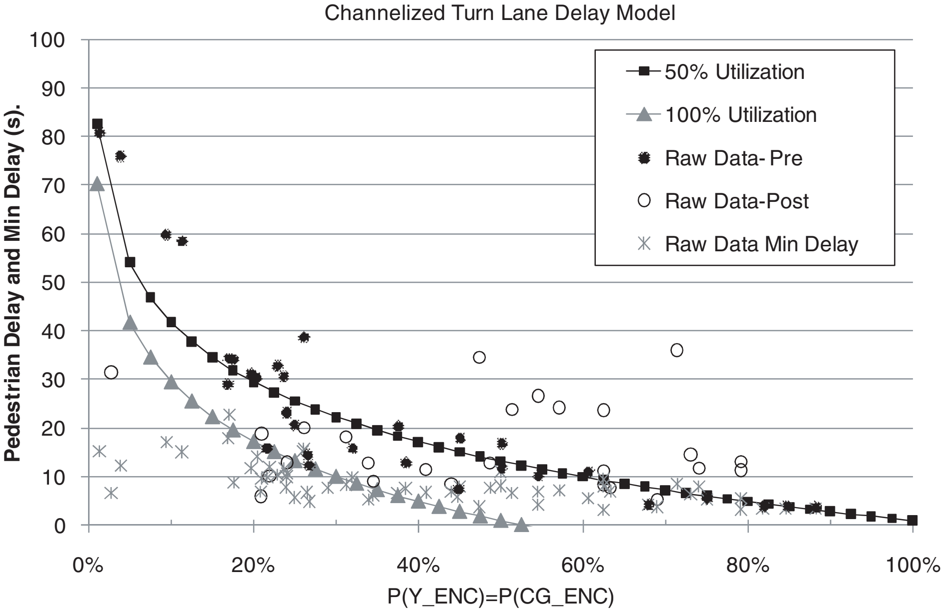
$$d_p = 0.89 - 17.75 * LN(P_{CROSS})$$

where

d_p = average pedestrian delay (s)

P_{CROSS} = the natural logarithm of the probability of crossing [= P(Y_ENC) * P(GO|Y) + P(CG_ENC) * P(GO|CG)].

The suggested delay model for channelized turn lanes predicts pedestrian delay as a function of the natural logarithm of P_{CROSS}, which is calculated from the four individual probability parameters. The overall model and the P_{CROSS} parameter are significant ($p < 0.0001$). The adjusted R-square value suggests that 79.3% of the variability in the delay is explained by the model, which is very high given that inter-participant variability of crossing performance was very high. Figure 25 shows the fit of the model against field-observed data. Since the LN(P_{CROSS}) term represents a combination of encounter and utilization parameters, it can be used to test the sensitivity of the different probability components. The two curves contained in Figure 25 therefore show the predicted delay for 50% opportunity utilization (both crossable gaps and yields) and 100% utilization. The latter approximates the delay a sighted pedestrian may have experienced if encountering the same crossing opportunities. The curves were created by varying P(Y_ENC) and P(CG_ENC) from 0 to 1.0 while keeping the values of P(GO|Y) and P(GO|CG) constant at 0.5 and 1.0.



This figure shows a chart of the developed mixed-priority delay model for the CTL. The chart plots the relationship between the probability of encountering yield and gap events on the x-axis and the pedestrian all crossing opportunities and pedestrians who only utilize 50% of opportunities. The graph further shows the field-observed data points for pretest and posttest, as well as the field-observed (theoretical) minimum delay for the pedestrians.

Figure 25. Graphical comparison of CTL delay model against field data.

The two curves are plotted against the raw average delay data for pretest and posttest conditions. Finally, the figure contains the theoretical average minimum delay for each data point. In interpreting the figure, the raw data should be compared against the 50% utilization curve, while the minimum delay data should be compared against the 100% utilization curve.

The figure shows that the general trends of the model delay curves fall within the area of observed data, as was suggested by the high model adjusted R-square value. The exponential model form predicts high delays when P_{CROSS} is in the range of 0 to 20%, corresponding to a very low occurrence of crossing opportunities (since utilization is fixed). As the availability of crossing opportunities increases, the delay drops, which is supported by the field data. The distinction between pretest (filled circles) and posttest (hollow circles) shows a general trend toward higher P_{CROSS} and lower delay after treatment installation. In this context it is important to emphasize that the treatment effect is not explicitly included in the model. While this was tried in model development, the treatment dummy variable was not significant with the P_{CROSS} variable also in the model. This indicates that any treatment effect *is implicitly represented in the variability of* P_{CROSS}. This finding gives confidence to the model form and allows its application beyond the treatments tested by varying the underlying probability terms. One example for this type of sensitivity analysis is the 100% utilization curve that hypothesizes the delay experienced by a (sighted) pedestrian who utilizes every opportunity. The trend for that curve fits well with the observed minimum delay raw data, which represents the minimum theoretical delay if the very first crossing opportunity was always utilized by a participant.

Single-Lane Roundabout Delay Model

A total of 40 participants were included in the analysis from three different single-lane roundabout sites. Each observation represents the average of four or more crossing trials at a particular site. With the distinction of entry versus exit crossings, the dataset contained 80 observations. However, four observations had to be excluded since these participants had one or more zero observations because they either didn't encounter any crossable gaps or because no drivers yielded for them. As a result, the final dataset contained 76 observations. No treatments were installed at any of the tested single-lane roundabouts, and consequently there is no posttreatment data.

Various model forms were tested and are discussed in detail in Appendix K. Model selection was guided by statistical significance (overall model significance, parameter significance, and adjusted R-square value) as well as practical significance (model simplicity, reasonableness of results, fit with field-observed data). Equation 2 shows the suggested pedestrian delay model.

Equation 2. Suggested pedestrian delay model for single-lane roundabouts.

$$d_p = 0.78 - 14.99 * LN\left(P_{CROSS}\right)$$

where

d_p = average pedestrian delay (s)

P_{CROSS} = probability of crossing $[= P(Y\_ENC) * P(GO|Y) + P(CG\_ENC) * P(GO|CG)]$.

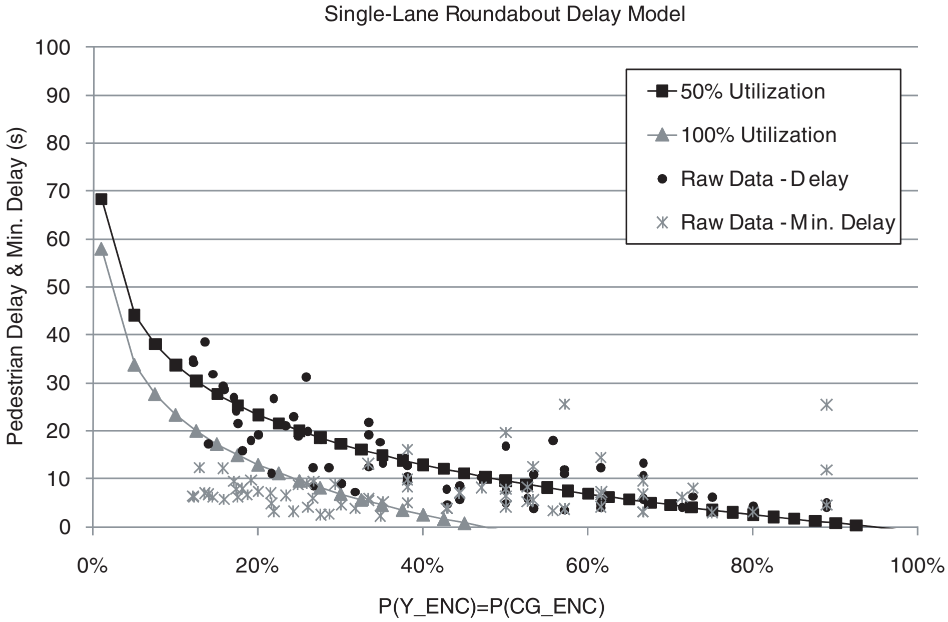
The suggested delay model for channelized turn lanes predicts pedestrian delay as a function of the natural logarithm of P_{CROSS}, which is calculated from the four individual probability parameters. The overall model and the P_{CROSS} parameter are significant ($p < 0.0001$). The adjusted R-square value suggests that 63.6% of the variability in the data is explained by the model, which is very high given that inter-participant variability of crossing performance was very high.

Figure 26 shows the fit of the model against field-observed data. Since the $LN(P_{CROSS})$ term represents a combination of encounter and utilization parameters, it can be used to test the sensitivity of the different probability components. The two curves contained in Figure 26 therefore show the predicted delay for 50% opportunity utilization (both crossable gaps and yields) and 100% utilization. The latter approximates the delay a sighted pedestrian might have experienced if encountering the same crossing opportunities. The curves were created by varying P(Y_ENC) and P(CG_ENC) from 0 to 1.0 while keeping the values of P(GO|Y) and P(GO|CG) constant at 0.5 and 1.0. The two curves are plotted against the raw average delay data for pretest and posttest conditions. Finally, the figure contains the theoretical average minimum delay for each data point. In the interpretation of the figure, the raw data should be compared against the 50% utilization curve, while the minimum delay data should be compared against the 100% utilization curve.

The figure shows that the general trends of the model delay curves fall within the area of observed data, as was suggested by the high model adjusted R-square value. The exponential model form predicts high delays when P_{CROSS} is low, corresponding to a very low occurrence of crossing opportunities (since utilization is fixed). As the availability of crossing opportunities increases, the delay drops, which is supported by the field data (black circles). Similar to the CTL model, the 100% utilization curve fits well with the observed minimum delay data.

Two-Lane Roundabout Delay Model

The two-lane roundabout model utilized different independent variables that are consistent with the revised analysis framework for two-lane approaches presented in Chapter 4. The reader may recall that crossing a two-lane roundabout requires the consideration of three different event conditions



This figure shows a chart of the developed mixed-priority delay model for the single-lane roundabout. The chart plots the relationship between the probability of encountering yield and gap events on the x-axis and the pedestrian delay in seconds on the y-axis. The graph shows two curves, representing pedestrians with 100% utilization of all crossing opportunities and pedestrians who only utilize 50% of opportunities. The graph further shows the field-observed data points for pretest and posttest as well as the field-observed (theoretical) minimum delay for the pedestrians.

Figure 26. Graphical comparison of single-lane roundabout delay model against field data.

for each lane (crossable gap, non-crossable gap, and yield) resulting in nine different combinations. A crossable situation is defined as encountering either a yield or a crossable gap. From these nine combinations, four yield crossable situations in both lanes: Yield–Yield, Yield–CG, CG–Yield, and CG–CG. There are four other combinations that have crossable situations in only one of the lanes (Yield–non-CG, CG–non-CG, non-CG–Yield, and non-CG–CG). The remaining combination has a non-crossable gap in both lanes. These combinations introduce new probability terms that are defined below:

- **PA_Dual:** This is the probability of encountering a crossable situation (i.e., crossable gap or yield) in *both* lanes.
- **PU_Dual:** This is the probability of utilizing a situation that has a crossable situation (crossable gap or yield) in *both* lanes.
- **P_Dual_Cross:** This is the probability of crossing when both lanes have a crossable situation, defined as PA_Dual times PU_Dual.

A total of 31 participants were included in the analysis, including pretest (18 participants) and posttest treatment (13). Each observation represents the average of 16 crossing trials [four round trips, each with crossing trials from curb to splitter island at entry (exit), from splitter island to curb at exit (entry), and going back] at each of two approaches of the two-lane roundabout. However a few of the observations had to be excluded from the dataset since the participant did not encounter any yields from drivers. As a result the final dataset contained 124 observations

Various model forms were tested and are discussed in detail in Appendix K. Model selection was guided by statistical significance (overall model significance, parameter significance, and adjusted R-square value) as well as practical significance (model simplicity, reasonableness of results, fit with field-observed data). Equation 3 shows the suggested pedestrian delay model.

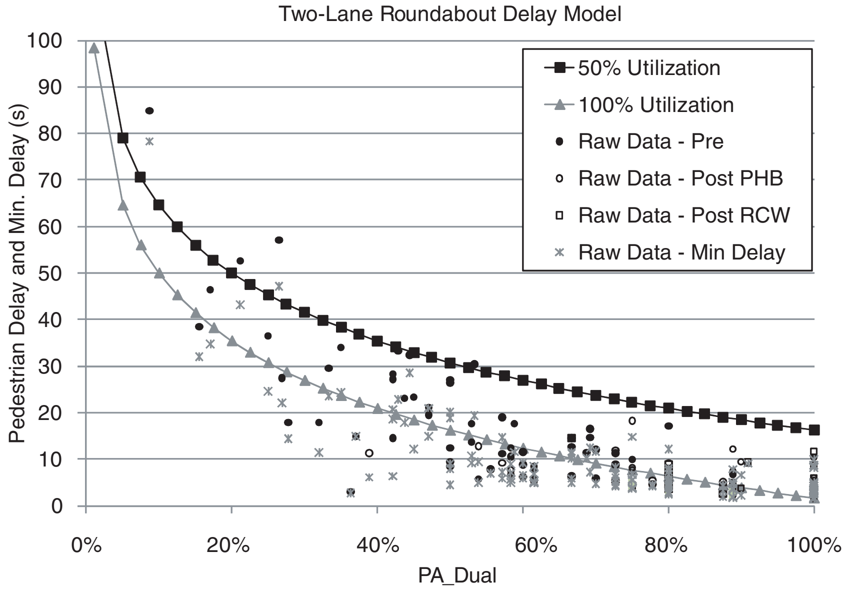
Equation 3. Suggested pedestrian delay model for two-lane roundabouts.

$$d_p = 1.9 - 21.0 * LN\left(P_{Dual\_CROSS}\right)$$

where

$\mathrm{d_p}$ = average pedestrian delay (s)
$\mathrm{P_{Dual\_Cross}}$ = probability of crossing when both lanes have a crossable situation in the form of a crossable gap or a yield (= PA_Dual * PA_Dual).

The suggested delay model for channelized turn lanes predicts pedestrian delay as a function of the natural logarithm of $\mathrm{P_{DUAL\_CROSS}}$, which is calculated from the availability and encounter probability of dual crossing opportunities. The



This figure shows a chart of the developed mixed-priority delay model for the two-lane roundabout. The chart plots the relationship between the probability of encountering a dual crossing opportunity (gap or yield in both lanes) on the x-axis and the pedestrian delay in seconds on the y-axis. The graph shows two curves, representing pedestrians with 100% utilization of all crossing opportunities and pedestrians who only utilize 50% of opportunities. The graph further shows the field-observed data points for pretest and posttest (RCW and PHB), as well as the field-observed (theoretical) minimum delay for the pedestrians.

Figure 27. Graphical comparison of two-lane roundabout delay model against field data.

overall model and the P_{CROSS} parameter are significant ($p < 0.0001$). The adjusted R-square value suggests that 78.7% of the variability in the data is explained by the model, which is very high given that inter-participant variability of crossing performance was very high.

Figure 27 shows the fit of the model against field-observed data. Since the LN(P_{DUAL_ROSS}) term represents a combination of encounter and utilization parameters, it can be used to test the sensitivity of the different probability components. The two curves contained in Figure 27 therefore show the predicted delay for 50% opportunity utilization and 100% utilization. The latter approximates the delay a sighted pedestrian might have experienced if encountering the same crossing opportunities. The curves were created by varying PA_Dual from 0 to 1.0 while keeping the values of PU_DUAL constant at 0.5 and 1.0. The two curves are plotted against the raw average delay data for pretest and posttest conditions. Finally, the figure contains the theoretical average minimum delay for each data point. In the interpretation of the figure, the raw data should be compared against the 50% utilization curve, while the minimum delay data should be compared against the 100% utilization curve.

The figure again shows a predicted decrease in delay with increase in the availability of dual crossing opportunities. The shape of the curves is characteristic of the logarithmic model form. In a comparison to the field-observed delay (filled circles), the 50% utilization curve appears to overpredict delay. This is because the field-observed utilization rates (of dual events) for blind pedestrians were very high at this site, on the order of 90% for both pretest and posttest. Consequently, the field-observed delay matches more closely with the 100% utilization curve, as it should. The 100% utilization curve expectedly is shifted downward compared to the 50% curve, corresponding to lower delay at the same PA_Dual encounter rate. The 100% curve matches well with the field-observed minimum delay values.

The field-observed data for the posttest with PHB and RCW installed show no observations at PA_Dual less than 40%, whereas the pretest data is distributed over almost the entire range. The corresponding delay figures for the posttest data points are low and match the predicted delay model. Consequently, the delay improvements of the PHB and RCW treatments are consistent with the increased PA_Dual probabilities.

Model Comparison

This section compares the selected mixed-priority delay models for the three facility types. Since the models for CTLs and single-lane roundabouts use the same variable definitions

Table 11. Comparison of delay models for three facility types.

	CTL	Single-Lane Roundabout	Two-Lane Roundabout
Intercept	0.89	–0.78	1.7*
$Ln(P_{Cross})$	–17.75**	–14.99 **	n/a
$Ln(P_{Dual\_Cross})$	n/a	n/a	-21.0**
Pr>F	<.0001	<.0001	<.0001
DF	1	1	1
R-Square	0.796	0.641	0.785
Adj. R-square	0.793	0.636	0.783

* Significant at $p < 0.05$

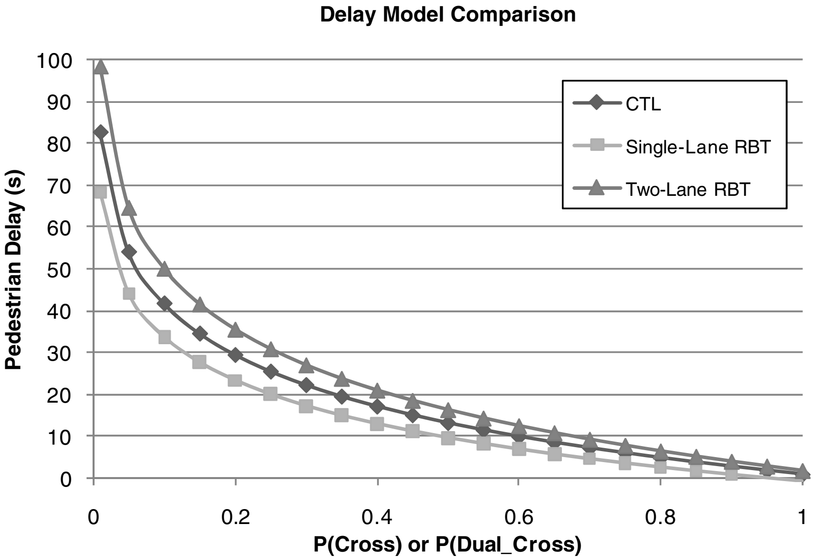
** Significant at $p < 0.01$

and model form, they are directly comparable. The two-lane roundabout model uses revised definitions for explanatory variables, but a general comparison is still possible. Table 11 shows the final delay models for the three sites for comparison.

All three models use natural-log transformed explanatory variables [LN(PCross) and LN(PDual_Cross)] with negative coefficients. Since the natural log of a low number is a large negative number [e.g., $\ln(0.1) = -2.3$], this results in a high positive prediction (of delay) at low probabilities. With increasing probabilities the absolute value of the natural log decreases, thus dropping the predicted delay. A greater coefficient therefore results in higher delays at low probabilities. For example, the fact that the CTL model has a higher absolute value coefficient (–17.75) compared to the single-lane roundabout (–14.99) indicates that CTL delay is always higher than the single-lane roundabout. However, due to the nature of the model, the relative difference is greater at low probabilities than at higher ones since the natural log decreases in absolute value [e.g., $\ln(0.9) = -0.1$]. As with a conventional linear regression model, the intercept shifts the curve upward (positive coefficient) or downward (negative coefficient). However, due to the relatively low absolute value of the intercept compared to the coefficient for Ln(PCross), the effect of the intercept on model form is negligible. In other words, in the general model for $y = a + b * \ln(x)$, the parameter "b" in this case weighs much more heavily than parameter "a."

Following this discussion, the models predict greater delay for channelized turn lanes than for single-lane roundabouts, assuming the same traffic patterns and pedestrian behavior. While the dependent variable for the two-lane roundabout model is slightly different, its coefficient (–21.0) suggests that delays are greater at two-lane roundabouts than at the other sites, assuming that traffic patterns and user behavior are fixed. These comparisons are illustrated in Figure 28, which shows the three delay curves as a function of the explanatory variables LN(PCross) and LN(PDual_Cross) on the x-axis.

As discussed above, the curve for two-lane roundabout delay is always higher than the CTL curve, which in turn predicts higher delays than the single-lane roundabout curve. Due to the natural-log transformed model form, the relative difference between the curves decreases with higher probabilities of crossing. All three curves expectedly approach a delay of zero as those probabilities approach 1.0 or 100%.



This figure shows a comparison chart of the three developed mixed-priority delay models for the channelized turn lane, single-lane roundabout, and two-lane roundabout. The chart plots the relationship between the probability of encountering a (dual) crossing opportunity on the x-axis and the pedestrian delay in seconds on the y-axis. RBT = roundabout.

Figure 28. Delay model comparison for three facility types.

The comparison does not mean that all two-lane roundabouts will always produce higher delays than any single-lane roundabout or CTL. It merely says that a pedestrian will experience higher delay at a two-lane roundabout than a single-lane roundabout (or CTL) when encountering the exact same traffic patterns and driver behavior and is furthermore capable of making the same judgments about gaps and yields. The actual performance of a particular site and the relative difference to other sites depends on the underlying probabilities that make up P_{Cross} and P_{Dual_Cross}. An approach for estimating these is discussed in the next section.

Table 12. Pedestrian LOS stratification, adopted from the HCM (TRB 2000).

	Delay Range (s/ped)		
LOS	Signalized	Unsignalized	Likelihood of Noncompliance
A	<10	<5	Low
B	≥10–20	≥5–10	
C	>20–30	>10–20	Moderate
D	>30–40	>20–30	
E	>40–60	>30–45	High
F	>60	>45	Very high

Model Application

The mixed-priority pedestrian delay models presented in this section can theoretically be applied to other sites with different geometries, traffic volumes, and pedestrian behavior. Clearly the application of any model beyond its realm of calibration can be risky, and professional judgment should be applied. In general, these models are not intended to serve as the sole determinant of pedestrian accessibility and should not be used in isolation. As this report discusses, pedestrian delay is only one aspect of accessibility, with pedestrian risk being another that is equally if not more important. Clearly, the risk to pedestrians or the fact that a crossing may be avoided entirely if the real or perceived risk is too high needs to be considered first and foremost. Further, Chapter 2 of this report discusses the other components of the crossing task, which include locating the crosswalk, aligning to cross, deciding when to cross, and maintaining alignment after the crossing is initiated. The delay models are focused on the third component and therefore do not capture any additional delays that may occur when a pedestrian is challenged to locate the intended crossing point.

Selecting Delay Thresholds

The application of delay models is associated with the challenge of defining thresholds for what is considered an acceptable wait time and whether these thresholds differ by facility type. The *Highway Capacity Manual* (TRB 2000) uses delay to stratify LOS for (sighted) pedestrians and other modes at signalized and unsignalized starting points. Logically, the HCM LOS tables could represent a starting point for the discussion of acceptable delay thresholds. The HCM table for signalized and unsignalized pedestrian crossings is presented in Table 12.

The table shows a stratification of LOS from A (best) to F (worst) using ranges of average delay per pedestrian for the crossing. From the HCM exhibits it is evident that the presumed level of acceptable delay is greater at a signalized intersection because the presence of the signal is associated with a certainty that a crossing opportunity will eventually present itself. Consequently, pedestrians may be more willing to accept greater delay at signals. However, the table recognizes qualitatively that the likelihood of pedestrian risk taking (i.e., jaywalking against the signal or accepting short gaps in traffic) increases with higher pedestrian delay. The HCM LOS stratification does not distinguish between one-stage and two-stage crossings, so it is assumed here that the thresholds are intended to be applied to the *entire crossing,* which in the case of roundabouts represents the sum of delay experienced at the entry and exit leg. At channelized turn lanes, the total crossing delay accordingly includes the delay at the main intersection and any additional CTLs that are in the path of the pedestrian.

It is important to emphasize here that (blind) pedestrian delay can also be measured directly from field observations, which is usually the preferred approach. Any theoretical model is participant to variability and error, and direct field measurements are likely to provide a more unbiased estimate of delay or any other parameter. In the absence of field data, the remaining challenge in the application of the mixed-priority delay models is to identify appropriate model inputs. This is the focus of the next sections.

Estimating Probability Parameters

The probability parameters that are used as the explanatory variables in the mixed-priority delay models can be estimated directly from field measurements or can be gleaned from the appropriate literature and traffic flow theory concepts. As with any model application, the use of field-measured probabilities is preferable since these give the analyst the greatest confidence. It is recognized that field measurements are often beyond the scope and budget of such analysis and are further precluded for newly planned locations. Field studies are also not applicable for sensitivity analyses that explore the potential impact of implementing pedestrian treatments to improve accessibility at a particular location.

The delay models for channelized turn lanes and single-lane roundabouts are based on the variable P_{Cross}, which is a function of the four probability terms P(Y_ENC), P(CG_ENC), P(GO|Y), and P(GO|CG). For two-lane roundabouts, the explanatory variable is P_{Dual_Cross}, which is a function of the availability and utilization of crossing opportunities in both lanes, PA_Dual and PU_Dual. An analyst can apply the delay models to new sites and conditions by estimating these parameters from field measurements or literature sources.

For the field measurement of the explanatory variables, the rate of driver yielding and the availability of crossable gaps can be measured using manual tally and stopwatch methods described in the ITE *Manual of Transportation Studies* (1994) or other sources. The estimation of yield and gap utilization rates is more difficult for blind pedestrians since it requires controlled field experiments. In the absence of field data, the results from this research can be used in the interim, which is discussed in more detail below. For sighted pedestrians, utilization rates of or near 1.0 can be assumed. For other special pedestrian populations, including children and the elderly, analyst judgment will be required until further research characterizes their behavior. A basic sensitivity analysis can ensure that a range of values are considered. In the absence of field data, probabilities can also be estimated from the literature, which includes findings from this research and other field studies, as well as theoretical traffic flow relationships.

Crossable Gap Encounters. 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, one can use the negative exponential distribution to estimate the probability of observing a time headway greater than t_c seconds, per Equation 4. This equation assumes random arrivals of vehicles. For non-random arrivals, other distributions are available (May 1990).

Equation 4. Estimating P(CG_ENC) from traffic flow theory (May 1990).

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

where

t_c = critical headway for crossable gap (s)

t_{avg} = average headway, defined as $t_{avg} = (3{,}600\ \text{s/h})/(\text{vph})$.

In the absence of pedestrian platoons, the critical gap for pedestrians can be calculated by Equation 5 following the HCM methodology.

Equation 5. Pedestrian critical gap after HCM Equation 18-17 (TRB 2000).

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

where

L = crosswalk length (ft),

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

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

Using the above relationship, the probability of observing a crossable gap in a stream of 400 vph at a 14-ft lane at a roundabout and a corresponding critical headway of $t_c = 14/3.5 + 2 = 6$ s is:

$$P(CG\_Enc) = P(headway \geq 6s) = e^{-\frac{t_c}{t_{avg}}} = e^{-\frac{6}{9}} = 51.3\%$$

Yield Encounters. The probability of encountering a yielding vehicle is a function of driver courtesy and 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 from the probability P(Y_ENC) used in the delay model, which is calculated on the basis of all encountered vehicles and is a better representation of the flow rate that a pedestrian is likely to experience. A reasonable approach for estimating P(Y_ENC) from P(Yield) is to subtract the probability of crossable gaps from the total number of vehicle events:

Equation 6. Estimating yield encounters from yield probabilities.

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

This approach ensures that the sum of P_{Y_ENC} and P_{CG_ENC} is less than or equal to 1.0, as is required by definition. The reader is referred to Chapter 4 for more detail on these event definitions.

Probability estimates for the probability of yielding (P_{Yield}) are available from research. A recent national survey on roundabout operations (Rodegerdts et al. 2007) has estimated yield probabilities for many single-lane and two-lane roundabouts. Table 13 shows observed ranges for single-lane approaches from that research along with findings from this project.

The table shows significant variation across yielding rates for the studied sites. The averages and ranges from NCHRP Report 572 represent five single-lane roundabouts. These were the only studied sites that featured notable pedestrian activity. It appears that the single-lane roundabout yielding rates observed during this project are much lower than the ones observed in that project. A potential explanation for this is the different levels of pedestrian use and associated driver courtesy. The statistics do, however, point to the general trend that yielding rates at the exit lane are often lower than at the entry lane.

Table 13. Yield probabilities (P_{Yield}), for single-lane approaches.

	Single-Lane Roundabouts					CTL
	NCHRP Report 572		NCHRP Project 3-78A Averages			NCHRP Project 3-78A Sites
	Average	Range	DAV-CLT	PS-RAL	GOL-PRE	
Entry Lane						26.1%
Curb–island	85%	65%–100%	10.8%	41.5%	65.6%	
Island–curb	90%	50%–100%				
Exit Lane						
Curb–island	71%	17%–100%	11.8%	32.8%	36.1%	
Island–curb	85%	33%–100%				

A comparison between roundabouts and the CTL studies under NCHRP Project 3-78A further points to low CTL yielding behavior at the tested sites. It is expected that a wider range of rates would be observed with a greater sample of CTL sites with varying geometry.

Gap and Yield Utilization. The remaining explanatory probability variables are the rates of utilization for yield and crossable gap opportunities. It was hypothesized above that most sighted pedestrians would be assumed to accept most or all first yield and crossable gap opportunities. Their rates of utilization for those events would therefore be assumed to equal 1.0. For blind pedestrians, utilization rates much lower than 100% have been observed in this research as well as in prior studies. Individual differences and unique auditory characteristics of different sites are expected to affect these rates. Tables 14 and 15 summarize the utilization rates observed at single-lane roundabout and CTL crossings in this research, respectively. Two-lane roundabouts are discussed separately.

The tables show average utilization rates for all sites in the range of 50% to 80%. The utilization rates are highest at the GOL-PRE single-lane roundabout. The statistics further show a large range of these 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. As discussed in Chapter 5, the installation of crossing treatments at the CTL had some impact on the utilization statistics. The installation of sound strips only (SS-ONLY) resulted in a slight decrease of yield utilization. The added use of a flashing beacon (SS+FB) increased both yield and crossable gap utilization.

Numerical Illustration for Single-Lane Roundabout. This section presents an example calculation for a single-lane roundabout that will be used by a population of blind pedestrians. The delay equation for a single-lane roundabout was given previously by Equation 2, which expands to:

$$
\begin{aligned}
d_p &= -0.78 - 14.99 * LN\left(P_{CROSS}\right) \\
&= -0.78 - 14.99 * LN\left(P_{Y\_ENC} * P_{GO|Yield} + P_{CG\_ENC} * P_{GO|CG}\right)
\end{aligned}
$$

where all terms are as defined previously.

To estimate the delay at a site, the analyst would first estimate the availability of yield and crossable gap opportunities. In this context, it is critical that these two probabilities use the same common denominator in the total number of vehicle

Table 14. Yield and crossable gap utilization rates at studied single-lane roundabouts.

	Single-Lane Roundabout					
	DAV-CLT		PS-RAL		GOL-PRE	
	Avg.	Range	Avg.	Range	Avg.	Range
P(GO|Y)						
Entry lane	64.1%	0%–100%	83.0%	50%–100%	82.8%	36%–100%
Exit lane	70.4%	0%–100%	87.8%	60%–100%	76.0%	25%–100%
P(GO|CG)						
Entry lane	66.3%	25%–100%	52.0%	0%–100%	83.2%	33%–100%
Exit lane	60.3%	33%–100%	63.6%	19%–100%	86.8%	40%–100%

Table 15. Yield and crossable gap utilization rates at studied channelized turn lanes.

		Average	Range
P(GO|Y)	PRE	51.9%	0%–100%
	POST-SS-ONLY	40.5%	10%–75%
	POST-SS+FB	64.6%	20%–100%
P(GO|CG)	PRE	61.8%	4%–100%
	POST-SS-ONLY	68.2%	6%–100%
	POST-SS+FB	89.3%	58%–100%

events. By definition, the sum of P_{Y_ENC} and P_{CG_ENC} can therefore never exceed 1.0, which would correspond to every vehicle event constituting a crossing opportunity. Since the two probabilities are related, it is expected that an increase in yielding will correspond to a lower fraction of encountered events being crossable gaps.

For the example, assume peak hour conflicting traffic flow at the site is 800 vph and the pedestrian critical gap is estimated at 6 s. At 800 vph, the average headway between vehicles is 3600/800, or 4.5 s. The probability of encountering a crossable gap greater than 6 s in this traffic stream is given by:

$$P(CG\_ENC) = P(headway \geq 6\text{s}) = e^{-\frac{t_c}{t_{avg.}}} = e^{-\frac{6}{4.5}} = 26.4\%$$

It is further assumed that the analyst knows from field studies that 30% of *the remaining traffic* is expected to yield. The probability of encountering a yield is therefore given by (100% – 26.4%) ∗ 30% = 22.1% of vehicle encounters.

Referring to Table 15, the analyst estimates that the utilization rates for yields and crossable gaps are 40% and 30%, respectively. This is about half of the average rates found in this research, and was selected to represent a more conservative and less skilled blind traveler:

$$d_p = -0.78 - 14.99 * LN(0.221 * 0.4 + 0.264 * 0.3) = 26.0 \text{ s}$$

Since this delay estimate is per crossing leg, the total approach delay is estimated at 52.0 s on average, which falls within HCM LOS = F for unsignalized crossings. This assumes that the behavioral parameters at the entry and exit legs are exactly the same. This simplifying assumption was only done for this example. In reality, the analyst should carefully consider the differences between entry and exit legs, including traffic volumes, vehicle speeds, and yielding behavior. As a comparison, a sighted pedestrian would have experienced a delay of:

$$d_p = -0.78 - 14.99 * LN(0.221 * 1.0 + 0.264 * 1.0) = 10.1 \text{ s}$$

Consequently, the delay for a blind pedestrian with the assumed lower utilization rates would be 2.6 times higher than for a sighted pedestrian facing the same traffic conditions and driver behavior.

A pedestrian treatment that improves driver yielding from 30% to say 75% would increase P_{Y_ENC} to (100% – 26.4%) ∗ 75% = 55.2% and would improve the delay for the blind pedestrian to:

$$d_p = -0.78 - 14.99 * LN(0.552 * 0.4 + 0.264 * 0.3) = 17.3 \text{ s}$$

Compared to the baseline delay of 26.0 s, this pedestrian treatment resulted in a 33.6% reduction in delay to the blind travelers. The total delay for both legs is reduced to 34.6 s. The treatments also helped sighted pedestrians and reduced their delay from 10.1 s to only 2.6 s on average:

$$d_p = -0.78 - 14.99 * LN(0.552 * 1.0 + 0.264 * 1.0) = 2.3 \text{ s}$$

The analyst can easily perform additional sensitivity analyses to test the hypothesized effects of other treatments or changes in the conflicting traffic volumes.

Estimating Probabilities for Two-Lane Approaches. Since the probability terms for two-lane roundabouts are different than for single-lane approaches, their estimation is discussed separately. The two-lane roundabout crossing process is characterized by the availability and utilization of dual crossing opportunities, which can be in the form of either a yield or a crossable gap in both conflicting lanes at the same time. The mixed-priority delay equation given above expands to:

$$\begin{aligned} d_p &= 1.9 - 21.0 * LN(P_{DualCROSS}) \\ &= 1.9 - 21.0 * LN(P_{A\_Dual} * P_{U\_Dual}) \end{aligned}$$

where all terms are as defined previously.

The probability of encountering either a crossable gap or a yield in both lanes, P_{A_Dual}, is calculated as follows.

1. The analyst calculates the likelihood of encountering a crossable gap in each lane, based on the estimated per-lane traffic volumes using Equation 4. The resulting probabilities are P_{CG1} and P_{CG2}, for lanes 1 and 2, respectively. Lane 1 is defined to be the one closest to the pedestrian.
2. The analyst estimates the probability of yielding in each lane, P_{Yield_Lane1} and P_{Yield_Lane2}, from field observations or literature.
3. The analyst calculates the probabilities of encountering a yield event in each lane P_{Y_ENC1} and P_{Y_ENC2} using Equation 6 and the results of steps 1 and 2.
4. The analyst estimates the probability of encountering a dual crossing opportunity in both lanes by the following equation:

Equation 7. Estimating yield encounters from yield probabilities.

$$P_{A\_Dual} = P_{Y\_ENC1} * P_{Y\_ENC2} + P_{Y\_ENC1} * P_{CG2} + P_{CG1} * P_{Y\_ENC2} + P_{CG1} * P_{CG2}$$

where

P_{A_Dual} = probability of encountering crossing opportunity in both lanes,
P_{Y_ENC1} = probability of encountering a yield in lane 1,
P_{Y_ENC2} = probability of encountering a yield in lane 2,
P_{CG1} = probability of encountering a crossable gap in lane 1, and
P_{CG2} = probability of encountering a crossable gap in lane 2.

The results from this research can again be used as guidance for the estimation of the probability of utilizing a dual crossing opportunity. Table 16 summarizes field-observed probabilities of encountering and utilizing dual crossing opportunities for the studied two-lane roundabout in the pretest condition.

The analyst can follow the procedure above to estimate the PA_Dual and PU_Dual probabilities for a two-lane roundabout and calculate the predicted average pedestrian delay using Equation 3 for two-lane approaches. A numerical example is not provided but is consistent with the example presented for single-lane roundabouts.

Impacts of Pedestrian Crossing Treatments

The underlying hypothesis of the NCHRP Project 3-78A analysis framework and these delay models is that there exists the ability to represent the impact of pedestrian crossing treatments through changes in the probability terms. This allows the analyst to quantify the impact of any treatment on pedestrian delay. Chapter 5 presented a detailed discussion of the measured impacts for the pedestrian treatments studied in this research. Consistent with the discussion in Chapter 2, various pedestrian treatments not tested in this research have a similar ability to reduce pedestrian delay.

Table 16. Field-observed performance at two-lane roundabout.

		Average	Range
PA_Dual	PRE	55.8%	15%–93%
	POST-RCW	76.9%	57%–100%
	POST-PHB	89.3%	72%–100%
PU_Dual	PRE	90.0%	44%–100%
	POST-RCW	98.1%	94%–100%
	POST-PHB	98.3%	83%–100%

Among the most common treatments are those intended to increase the probability of drivers to yield to pedestrians, which was one of the key focus areas of NCHRP Report 562 (Fitzpatrick et al. 2006). While data collection in that research was focused on midblock crossings, the results provide an overview of the average and range of yielding rates observed for different treatments across the country. The reader is encouraged to consult that and similar research for further information.

Delay Model Discussion

The previous section demonstrated the application of a framework based on pedestrian and driver behavioral parameters for estimating pedestrian delay at single- and two-lane roundabouts as well as at channelized turn lanes. The underlying dataset was obtained from controlled experiments using more than 100 blind participants at seven different sites. The focus on blind pedestrians provided a framework that distinguished between available crossing opportunities and the actual utilization of these opportunities. A dataset containing only sighted pedestrians would not be expected to capture the utilization effect.

The resulting delay models are statistically significant and produce good estimates of pedestrian delay that match observed field data. The underlying probability terms can be estimated from field observations for other sites or can be estimated from literature or traffic flow theory concepts. The resulting models allow the analyst to distinguish delay encountered at CTLs, single-lane roundabouts, and two-lane roundabouts. It further allows the analyst to represent the impact of pedestrian crossing treatments on delay.

Extension to Safety Modeling

As discussed earlier in this chapter and emphasized throughout this report, delay is only one factor when evaluating the accessibility and usability of a crosswalk. Another, potentially more critical aspect is the safety or risk associated with crossing at a particular location. This report uses the measure of O&M interventions to quantify the risk involved in crossing decisions by blind study participants. Clearly, it would be desirable to develop study extension tools for the assessment of pedestrian safety, similar to the delay models described above.

The development of predictive models for pedestrian risk or safety is constrained by a limitation of the risk performance measure of O&M interventions. Since interventions are very rare events, it is difficult to apply the regression-based modeling approach to this measure. The reason is that most of the observations result in a dependent variable value of zero (no interventions) while being associated with a range of underlying yield, gap, and utilization probability terms.

The resulting usable dataset for non-zero intervention crossing events is therefore very small. Recognizing that the event of an O&M intervention can be treated as a binary event (yes/no), it would be feasible to apply a logistic regression approach to these data. However, it is unclear how useful such models would be to practitioners.

An alternative and potentially more promising approach for safety modeling is feasible with the introduction of new dependent variables for pedestrian risk. Since the biggest limitations of the O&M intervention measure are its binary nature and rare occurrence, a revised variable should be continuous and frequently observable.

In particular, the project team discussed the use of two variables that meet these criteria. The first is the theoretical *time to collision* of pedestrian and vehicle in seconds, which is calculated from the speed and position of the vehicle at the instant the pedestrian steps into the crosswalk. The second is the *necessary deceleration rate* in feet per second squared that is necessary for the vehicle to come to a stop before the crosswalk. This measure is also calculated from the speed and position of the vehicle at the time the pedestrian steps into the crosswalk. This metric is further related to standard engineering signal timing practice, where a similar deceleration rate is used to calculate the length of the yellow interval at signals (ITE 2009).

The development of these measures requires real-time field measures of vehicle speed and position that were not available in this study. The feasibility of this approach has been demonstrated in other research (Schroeder 2008), where it was used to develop predictive models for driver yielding and pedestrian gap acceptance at unsignalized crossings. The approach is being explored in ongoing research on the accessibility of complex intersections to pedestrians who are blind (NIH 2010).

Simulation Approach

The NCHRP Project 3-78A analysis framework fits within the context of modern microsimulation tools. These software tools work on the basis of algorithms that describe driver behavioral rules for car following, lane changing, gap acceptance, and routing. Many of the commercially available products further allow the user to code both motorized and non-motorized transportation modes. The models differ in the specifics of how the interaction between vehicles and pedestrians is modeled and how much flexibility the user has in modifying and calibrating behavioral parameters. However, most models apply some sort of a gap acceptance algorithm to model pedestrians selecting gaps in traffic or to model drivers yielding to pedestrians. Depending on the model, the user also may have the ability to model mixed-priority situations where some drivers yield and some pedestrians cross in large gaps, as was discussed in the previous section. This distinction is critical to the implementation of the NCHRP Project 3-78A analysis framework. Furthermore, it will be necessary to represent different populations of drivers (courteous or not) and pedestrians (blind and sighted) to adequately capture the crosswalk interaction as observed in this study.

Assuming that a particular model can adequately address these aspects and can be calibrated to represent specific behavioral and traffic conditions, a simulation analysis is ideally suited to extrapolate performance results to other geometry and traffic patterns. The approach is also ideally suited for conducting sensitivity analyses of different parameters. In effect, a simulation-based analysis represents a second option for extending the field results from NCHRP Project 3-78A to other conditions. The first extension is of course the use of the delay models discussed in the previous section. Simulation has the added benefit that it can evaluate unique traffic characteristics, the impacts of nearby intersections, or the use of pedestrian signals (or PHBs) at the crosswalk in question. Finally, simulation models are increasingly used to perform surrogate safety analysis based on vehicle trajectories (FHWA 2008).

It is beyond the scope of this project to discuss in detail the variety of simulation tools available and to what extent they capture the interaction of pedestrians and vehicles at crosswalks. The focus of this section is to discuss the use of simulation analysis in two principal ways:

1. How to represent the analysis framework in simulation and findings from a sensitivity analysis of different behavioral and traffic-related model parameters. The objective is to guide other efforts of those who wish to further extend results from this research in a simulation environment. This section is primarily based on the work published in Schroeder and Rouphail (2007).
2. A detailed analysis of different signalization options at single-lane and two-lane roundabouts, including a comparison of PHB and conventional signals, one-stage and two-stage crossings, and different crosswalk geometries. The analysis is performed using calibrated representative models of a single-lane and a two-lane roundabout and explores operations for a range of vehicle and pedestrian volumes. The emphasis is on pedestrian-induced vehicle delay and queuing impacts with the objective to provide decision support for agencies that are considering signalization as one of the treatments at roundabout pedestrian crossings. This section is primarily based on the work published in Schroeder, Rouphail, and Hughes (2008).

Applying the Framework to Simulation

The NCHRP Project 3-78A analysis framework uses the principles of gap and yield availability as well as the rate of utilization of both types of crossing opportunities. The availability parameters represent characteristics of the traffic stream and are a function of traffic volumes, speed, and driver behavior. The utilization parameters are pedestrian behavior attributes that describe a pedestrian's ability and willingness to cross in a yield or gap situation. The analysis framework further uses the performance measure of delay and risk to quantify the pedestrian's ability to cross at a particular location.

The four availability and utilization probability parameters serve as *inputs* when the analyst sets up the simulation model. The analyst codes these after defining model geometry, traffic control strategies (signals), volumes, and other inputs. The remaining delay and risk performance measures are model *outputs* that are calculated from the simulation. It is beyond the scope of this report to describe the details of simulation modeling and the wide variety of modeling and calibration parameters that are available to the analyst. The FHWA has extensive resources available through the "Traffic Analysis Toolbox" (2010) that the analyst can use for further information on simulation modeling, calibration, and validation. The remainder of this section focuses on the proposed approach for modeling the interaction between pedestrians and vehicles.

Modeling Treatments

Based on the framework described above, the purpose of a treatment is to enhance or minimize delay and risk for pedestrians without negatively affecting traffic flow. It was hypothesized and demonstrated that the functional effect of a treatment can be described through a combination of the four underlying probability parameters. This can be done in one of four ways:

1. **Increasing the occurrence of driver yielding:** Previous research implies that slower speeds, increased driver awareness, and education/enforcement may be able to achieve this. Some natural speed reduction also occurs at high flows. Treatments addressing yielding could include warning signs, flashing lights, or raised crosswalks.
2. **Increasing the occurrence of crossable gaps:** It is unclear if there are treatments whose sole purpose is an increase in the availability of crossable gaps, but a number of situations will have an impact, including upstream signals or more conservative driver behavior. Ultimately, the biggest factor affecting this parameter is the amount of conflicting traffic.
3. **Increasing the probability of yield utilization:** Treatments may help blind pedestrians and others to more reliably detect the presence of yielding vehicles or increase their level of confidence in accepting yields. The list of potential treatments includes pavement sound strips, surface treatments, and automated yield detection technology.
4. **Increasing the probability of gap utilization:** There may be treatments that enable pedestrians to perform better gap judgment so as to decrease the frequency of risky or overly conservative decisions. Examples include improved lighting conditions and automated gap detection technology.

The functional effect of a treatment installation is represented in simulation through a net increase (or decrease) in one or more of the probability terms. The proposed approach for modeling treatments is therefore *implicit,* through changed behavioral parameters, rather than *explicit,* through a building block included in the simulation tool. The one exception to this approach is when a treatment involves the use of signalized traffic control. This aspect is discussed toward the end of this chapter.

Setting up Behavioral Parameters

This section discusses how the four probability parameters could be implemented in a simulation. Differences among drivers and pedestrians are best represented through the use of multiple vehicle and pedestrian classes. For example, two driver classes may be modeled: those with and those without the propensity to yield. Similarly, two or more pedestrian classes may be modeled with different gap acceptance thresholds. In particular, the four probability parameters would be modeled as follows:

- The *availability of yielding* should be modeled through the use of multiple vehicle classes. The gap acceptance algorithm at the crosswalk that effectively tells drivers to look for gaps in the pedestrian traffic will lead a potential yielder to slow in the presence of a pedestrian. The vehicle classification of whether or not a driver is a potential yielder is stochastically assigned to each vehicle as it enters the simulated system. Note that these are actually "potential yielders" since some vehicles tagged as yielders may not encounter a pedestrian at the crosswalk or may be too close to the crossing to be able to yield when the pedestrian shows up. This probability will vary for the entry and exit legs of a roundabout and for different sites. Simulation models vary in their ability to apply customized gap acceptance algorithms for different simulated crossings.
- The *availability of a crossable gap* is determined from the headway distribution of traffic upon entering the system. This probability is implicit in the individual vehicle generation, and the gap sizes can be tracked by the model at any point in the simulated system. Some tools may have the flexibility of coding a custom headway distribution. Further, the headway arrivals at a crosswalk will be affected by upstream signals. If significant vehicle platooning is observed at a crosswalk, this effect should be accounted for in the simulation.

- The *propensity to utilize yields* is also stochastically assigned to each pedestrian as he or she arrives at the crossing location. This value will depend on whether the simulated pedestrian is blind or sighted (also assigned stochastically based on their respective volumes) and whether natural or augmented yield detection systems are in place. This aspect of the interaction is likely to be the most challenging to represent in simulation.
- The *utilization of crossable gaps* is handled through a gap acceptance algorithm, and different gap thresholds will be assigned to different populations of pedestrians. The challenge here lies with the fact that most simulation gap acceptance algorithms are based on minimum gaps, to the effect that a pedestrian will always utilize any gap greater than the minimum. To represent a utilization rate of less than 100%, additional customization may be necessary, which depends on the particular model used.

Model Calibration and Validation

The quality of the simulation analysis results relies on correct modeling inputs and adequate calibration and validation of model outputs. Model *inputs* are defined as those parameters that always need to be collected in order to develop a simulation model. These parameters include detailed site geometry, origin–destination traffic and pedestrian volumes, traffic composition, and signal timing. In addition, *calibration parameters* are available that have default settings included in the model but that can and should be customized by the user. These include speed distribution, gap acceptance behavior, gap distribution, yielding behavior, and yield utilization. In most cases, these parameters are adjusted (i.e., calibrated) to ensure that the model accurately represents field conditions. Finally, *validation parameters* are model *outputs* that allow the modeler to compare the model to field conditions or other models. Validation parameters include travel time, delay, queuing, and risk. In other words, model validation is achieved by altering calibration parameters and comparing the validation parameters to field conditions; input parameters stay constant throughout the calibration/validation process.

For model validation, simulation outputs are either compared to field-collected data or to outputs from other software packages for roundabouts and signalized intersections. These traffic analysis models are mostly designed for the analysis of vehicle traffic and are limited in their ability to model mixed-priority pedestrian–vehicle interaction. Consequently, the use of these traffic analysis tools is primarily to ensure that the vehicle operations in the simulation are modeled correctly. The analyst will have to rely on field observations or expert judgment to validate pedestrian results.

The following list of model **input parameters** needs to be collected to set up the initial simulation model:

- **Geometry:** The general geometry of the particular roundabout or CTL is often available in the form of a design drawing or a scaled aerial photograph. Geometric data of the site include correct lane widths and crosswalk locations.
- **Origin/destination (O/D) volumes by lane:** The typical simulation analysis uses traffic and pedestrian volumes for a duration of one hour. The flows in the model should represent actual turning percentages by approach (and by lane in the case of a two-lane roundabout).
- **Traffic composition:** The traffic composition at each site includes the percentage of heavy vehicles and the presence of special driver and/or pedestrian classes (yield/no yield or safe/risky).
- **Signal timings:** Where applicable, signal timings in the model are based on the actual signal timing plan for the intersection or, if necessary, on field measurements of average green times. In some cases, as in the evaluation of proposed treatments, signal timing reflects the proposed operation of the signal.

The following parameters are used for **calibration** to match the operations in the model to field conditions.

- **Speeds:** The modeler can input field-collected data on average vehicle speeds on the approaches upstream of the crosswalk, the entry to the roundabout, in the circulating lane of the roundabout, and in the turn lane. If actual speed data cannot be obtained, the posted speed limit can be used to infer a speed distribution on the approaches, and the literature (FHWA 2000, AASHTO 2004) can be used to approximate speeds in the roundabout or turn lane.
- **Gap acceptance:** Gap acceptance parameters for pedestrian crossings and for vehicle merges (into the roundabout or downstream traffic at a CTL) can be obtained either from field data or from sources in the literature. The model can include distributions of gap acceptance times by coding multiple vehicle and/or pedestrian classes. In this fashion it is possible to model pedestrians who make risky decisions, pedestrians with average behavior, and pedestrians with poor gap detection (who need very long gaps to cross).
- **Driver yielding (potential):** Different classes of drivers will be coded to achieve a certain percentage of potential yielders. Driver behavior will be based on observations at the site with help from sources in the literature.
- **Yield detection:** As discussed previously, some blind pedestrians may not be able to accurately detect drivers yielding for them at the crosswalk. The proportion of this group of pedestrians is a calibration parameter.
- **Headway distribution:** Modeling a user-defined headway distribution may be necessary in some occasions, for example if an upstream signal causes platoon arrivals of vehicles or if class changes on campus cause pedestrians to arrive in groups.

Finally, the following simulation outputs are proposed for model **validation:**

- **Travel times:** Simulation tools can estimate travel times on user-specified segments that can be used to compare actual travel times obtained in the field and so validate uncongested operations at the sites. Travel time data can be obtained as an average over the analysis period, separated by pedestrian/vehicle class or as raw data for each individual pedestrian/vehicle.
- **Delay times:** Vehicle and pedestrian delays in the defined travel time segments are estimated by subtracting the theoretical (undelayed) travel time from the actual travel time through a given segment. These data can be obtained as an average over the analysis period separated by pedestrian/vehicle class or as raw data for each individual pedestrian/vehicle and can be used to validate congested operations. It is also possible to validate using stopped delay.
- **Queue lengths:** The simulation tools generally provide estimates of average vehicle queues at a specified location that can be compared with field measurements. This measure may be most helpful in validating approach queuing at roundabouts.
- **Driver yielding (actual):** It is hypothesized that the number of actual yielders is significantly lower than the number of potential yielders entered in the model. In order for a yield to occur, the event of an approaching potential yielder needs to coincide with the presence of a pedestrian at the crosswalk and with sufficient time for the driver to decelerate at a comfortable rate. By comparing the fraction of actual yield events, the analyst can validate the assumptions used to derive the relationship between actual and potential yielders.

Measures of Risk from Simulation

It is further possible to use a simulation-based analysis approach to obtain an estimate of pedestrian risk by extracting the occurrence of pedestrian–vehicle conflicts. The FHWA surrogate safety assessment methodology (SSAM) is a post-processing tool that can interpret outputs from simulation tools and quantify the number of *conflicts* observed in the simulation (FHWA 2008). A conflict in this case is defined by one of several performance measures, including the time to collision. A methodology for estimating pedestrian–vehicle conflicts from simulation independent of SSAM is discussed in Schroeder and Rouphail (2006), which is also included in Appendix I.

Illustrative Example

This section is intended to demonstrate the proposed approach for modeling the interaction of pedestrians and drivers at unsignalized crosswalks in simulation. To illustrate the use of multiple vehicle and pedestrian classes, the two populations are divided into several groups. Vehicles are categorized as either *yielding* or *non-yielding* drivers, P(Y). Pedestrians are categorized into *blind* and *sighted* groups and within those groups in categories with different gap acceptance parameters—*risky, typical,* and *conservative*—where critical gap times are increasing in that order.

It will generally be assumed that most sighted pedestrians will make *typical* decisions, while blind pedestrians will be more strongly represented at either extreme. As crossing treatments are implemented at a facility, more pedestrians will shift away from *risky* and *conservative* decisions, thereby reducing conflicts and delay, respectively. In the following, we will assess the operational impacts of six treatment functionalities:

- **No control (NC):** This configuration represents the default interaction in a simulation model without any interaction between modes. Delay is a function of car-following parameters only, and risk is the result of random arrivals at the conflict point.
- **Unassisted crossing (UA):** Pedestrians and drivers are assigned priority rules that govern the interaction. Pedestrians have different gap acceptance parameters, and some drivers will yield if encountering a pedestrian. No further treatments are implemented.
- **Yield sign for drivers (YS):** The likelihood of drivers yielding is increased through treatments such as a raised crosswalk, warning signs, pedestrian flashers, enforcement, or education measures. It is assumed that the treatment has no effect on pedestrian behavior.
- **Vehicle detection (VD):** Some treatments will help blind pedestrians to more effectively detect the arrival of a vehicle. The assumption is that this will enable them to make better (safer and more efficient) crossing decisions. Examples include a gap-detection system and noise-generating rumble strips. It is assumed that driver behavior is not affected.
- **Yield sign and vehicle detect (YSVD):** This treatment category combines YS and VD treatments to increase driver yielding and improve the vehicle detection capabilities of blind pedestrians. Examples include a combination of automated vehicle detection with a pedestrian flasher or rumble strips in the approach of a raised crosswalk.
- **Perfect information (PI):** This configuration represents perfect unsignalized crossing conditions from a pedestrian perspective. Pedestrian delay and risk are minimized because 100% of vehicles yield to pedestrians. This form of driver behavior may represent a strictly enforced right-of-way law.

The six treatment scenarios are implemented in the simulation at a CTL location for a one-way, one-lane pedestrian crossing, using assumed run-specific pedestrian and driver

Table 17. Input parameters for simulation scenarios.

Treatment Functionality (Assume 100% Yield Detection)		Run-Specific Attributes						
		Pedestrians						Drivers
		50 Sighted Pedestrians per Hour			50 Blind Pedestrians per Hour			300 Vehicles per Hour
		P(C)	P(A)	P(R)	P(C)	P(A)	P(R)	P(Y)
NC	**No Information**	n/a	n/a	n/a	n/a	n/a	n/a	0%
UA	**Unassisted Crossing**	5	90	5	10	70	20	20%
YS	**Yield Sign for Drivers**	5	90	5	10	70	20	50%
VD	**Vehicle Detect for Pedestrians**	5	90	5	0	90	10	20%
YSVD	**Yield Sign and Vehicle Detect**	5	90	5	0	90	10	50%
PI	**Perfect Information, Everybody Yields**	0	100	0	0	100	0	100%

P(C)	Probability of **conservative** pedestrian crossing behavior. Pedestrian will accept gaps of **12 s or more.**
P(A)	Probability of **average** pedestrian crossing behavior. Pedestrian will accept gaps of **6 s or more.**
P(R)	Probability of **risky** pedestrian crossing behavior. Pedestrian will accept gaps of **3 s or more.**
P(Y)	Probability of drivers yielding to pedestrians (percentage of **potential yielders**).

attributes (Table 17). For illustrative purposes the implementation was tested and executed in the VISSIM simulation package (PTV 2005), but the approach should be applicable to other simulation tools as well.

It is assumed that the *typical* pedestrian has a critical lag of 6 s, which is considered safe compared to the actual crossing time of about 5 s at a walking speed of 4 ft/s. Accordingly, *conservative* pedestrians are assigned a longer critical lag value (12 s) and *risky* pedestrians have a short critical lag of only 3 s. The resulting delay and risk measures of effectiveness (MOEs) from 10 simulation replications per scenario are shown in Table 18.

The tables suggest that an increased likelihood of drivers yielding (case YS) decreases the percentage of conflicts. Improving VD for pedestrians appears to slightly increase observed conflicts compared to the unassisted case. Looking at the large standard deviations of the risk estimates, it cannot be stated if this is a real effect at the given sample size. This suggests the need for large sample sizes in the model repetitions to show significant effects when evaluating actual treatments.

In comparison, the delay MOEs suggest that as drivers yield more, delay for pedestrians decreases while driver delay increases. The table also indicates that the percent of actual driver yields is considerably less than the specified percent of theoretical yielders. This finding is expected at low pedestrian volumes since the majority of drivers do not encounter a pedestrian waiting at the crosswalk. This observation suggests challenges to estimating the required model input of potential yielders [P(Y)] from field observations of actual yielders.

This sample analysis shows that it is possible to use microsimulation models to extract conflict and delay data for pedestrian–vehicle interaction as a function of run-specific attributes of the two groups. The approach describes the interaction of the two modes in terms of four probability parameters: the likelihood of crossable gap occurrence [P(G)], the likelihood of gap detection [P(GD)], the likelihood of driver yielding [P(Y)], and the likelihood of yield detection [P(YD)]. From a preliminary analysis, it appears that the delay and conflict estimates produced by the model in fact follow expectations. For further information the reader is referred to the paper included in Appendix I.

Simulation-Based Analysis of Signalized Crosswalks

The aforementioned approach for describing pedestrian–vehicle interaction in a microsimulation environment applies to all unsignalized crosswalks, where the interaction is governed by the four assumed probability parameters. For signalized crossings, simulation tools already incorporate algorithms to replicate the way real-world traffic signals function and operate. Consequently, these built-in algorithms should be used when a signalized crosswalk is to be evaluated.

Table 18. Measures of effectiveness from simulation.

Treatment Functionality (Assume 100% Yield Detection)		Measures of Effectiveness (Average of 10 VISSIM Runs)									
		Actual Driver Yield – % Yield		Pedestrian Risk Lead, %		Pedestrian Risk Lag, %		Pedestrian Delay (s)		Vehicle Delay (s)	
		Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
NC	No Control	0.0%	0.00%	27.0%	5.20%	19.3%	2.40%	0.0	0.00	2.4	–
UA	Unassisted Crossing	3.8%	0.99%	2.1%	0.70%	0.5%	0.70%	4.4	0.28	3.1	0.32
YS	Yield Sign for Drivers	9.3%	1.16%	1.0%	0.80%	0.2%	0.70%	4.1	0.20	4.2	0.29
VD	Vehicle Detect for Pedestrians	3.7%	0.84%	2.7%	1.40%	0.2%	0.70%	4.3	0.37	3.1	0.27
YSVD	Yield Sign and Vehicle Detect	9.0%	1.33%	1.0%	1.00%	0.2%	0.70%	3.9	0.27	4.2	0.31
PI	Perfect Information, Everybody Yields	15.0%	2.00%	0.0%	0.00%	0.0%	0.00%	3.5	0.30	5.4	0.41

Depending on the specific signal strategy (i.e., a conventional signal versus a pedestrian hybrid beacon), it may be necessary to customize the signal control logic to some extent. The analyst should have a thorough understanding of how the signal is or will be implemented in the field before attempting to represent it in simulation. Particular attention should be paid to whether the signal operates in "free" operation or whether it is in some way coordinated with other pedestrian signals (two-stage crossing) or with the vehicle signal at the main intersection (for channelized turn lanes).

The analyst should further consider whether actual driver and pedestrian behavior is consistent with the way it is intended by the signal. For example, it was observed at the PHB installation in this project that some pedestrians crossed before the "Walk" phase came on while others waited until the "Flashing Don't Walk" before they felt comfortable crossing. In other words, pedestrians used the signal as a crossing aid, but by no means as the sole means of determination for stepping into the roadway. Similarly, some drivers were observed to proceed despite a red signal indication. For modeling the vehicular impact of the PHB signal, it is of particular importance to adequately represent driver behavior. That signalization strategy is intended to result in more efficient vehicle operations by allowing drivers to proceed during the "Flashing Red" phase if no pedestrian is in the crosswalk. Clearly, the estimated vehicle delay for this strategy is principally tied to the level of understanding of and compliance with this phasing scheme.

With these considerations in mind, simulation tools can readily be used to estimate the effect of signals on pedestrian and vehicle delay. Even without fully capturing the behavioral aspects related to the signal, a simulation-based analysis is a great tool for a relative comparison of different signal strategies.

Pedestrian Signals at Roundabouts

This section summarizes a detailed sensitivity analysis of pedestrian signalization options for modern roundabouts performed in simulation. The discussion is based on work published in Schroeder et al. (2008), which is included in Appendix L for quick reference.

The objective of this sensitivity analysis is to explore the *pedestrian-induced impacts* of different signalization strategies at modern roundabouts in a simulation environment. The analysis focuses on six analysis dimensions:

1. **Roundabout geometry:** The analysis includes a single-lane and a two-lane roundabout.
2. **Crosswalk location:** The analysis includes three alternative crosswalk geometries. The *proximal* crossing is the standard crosswalk location set back from the circulating lane by one vehicle length (~20 ft). The zigzag configuration moves the exit portion of the crosswalk to a distance of three vehicle lengths (~60 ft) from the circulating lane to

Table 19. Test matrix of treatment combinations (source: Schroeder et al. 2008).

Crosswalk Location	Crosswalk Staging	Single-Lane Roundabout	Two-Lane Roundabout
Proximal Crossing	**One stage**	Yes	Yes
	Two stage	No	Yes
Zigzag Crossing	**One stage**	No	No
	Two stage	Yes	Yes
Distal Crossing	**One stage**	Yes	No
	Two stage	No	Yes

provide additional queue storage on the exit leg. The *distal* crossing location moves the entire crosswalk to a distance of five vehicle lengths (~100 ft) from the circulating lane.

3. **Signal staging:** The analysis includes single-stage and two-stage phasing schemes as appropriate.
4. **Signalization strategy:** The analysis includes a conventional pedestrian signal and a pedestrian hybrid beacon (i.e., HAWK signal). The analysis assumes full understanding of and compliance with the signal phases, which is reasonable for a relative comparison. For an absolute assessment of the delay impact, some variation in behavior should be considered.
5. **Vehicle volumes:** The analysis considers a range of vehicle volumes, categorized as below capacity, at capacity, and slightly above capacity.
6. **Pedestrian volumes:** The analysis considers two levels of pedestrian volumes (10 and 50 pedestrians per hour) relative to the baseline of no pedestrians.

Appendix L provides a more detailed description of the different model scenarios. Table 19 summarizes the tested combinations of the dimensions of roundabout geometry, crosswalk location, and signal staging.

The table demonstrates that some of the combinations were not tested because they were considered impractical. For example, a two-stage crossing at a single-lane roundabout proximal crosswalk is expected to result in low compliance and therefore wasn't tested. Similarly, a one-stage crossing was not tested for the zigzag configuration since the elongated splitter island provides a natural separation between the two stages of the crossing. For each of the checked cells, the analysis considered all combinations of the remaining three dimensions (signalization strategy, vehicle volumes, and pedestrian volumes). In addition, the analysis included an additional volume sensitivity that was intended to capture the effect of even higher pedestrian flows of up to 300 pedestrians/hour. The analysis used the average results from 10 simulation replications in each scenario. All runs evaluated the effect of one signalized crosswalk being installed at the busiest approach to the roundabout.

The analysis results provide a quantitative comparison of different signalization options for pedestrian crossings at one-lane and two-lane roundabouts, all of which intended to improve access for blind pedestrians. Table 20 highlights a subset of the results for the case of 50 pedestrians/hour crossing at the signalized two-lane roundabout crosswalk. Results are shown for below-capacity and at-capacity vehicle volumes. These two-lane roundabout scenarios were selected because they directly relate to the most likely application of roundabout pedestrian signals. Additional results are provided in Appendix L.

The results indicate that innovative signalization treatments, including the PHB and two-stage crossings, can significantly decrease vehicle delay. With 50 pedestrians/hour at the two-lane roundabout, a proximal single-stage pedestrian-actuated signal resulted in pedestrian-induced vehicle delays of 14.2 s per vehicle in the below-capacity scenario and 68.4 s for the at-capacity case. The use of a PHB at the same location

Table 20. Sample results of roundabout signalization sensitivity analysis.

Two-lane Roundabout, 50 peds/hour			Below Capacity		At Capacity	
Crosswalk Location	Signal Staging	Signal Strategy	Delay per Vehicle (s)	% Change over Base	Delay per Vehicle (s)	% Change over Base
Proximal	Single stage	Ped. signal	14.2	Base	68.4	Base
		PHB	6.3	–56%	39.4	–42%
	Two stage	Ped. signal	4.1	–71%	24.4	–64%
		PHB	1.5	–89%	5.5	–92%
Zigzag	Two stage	Ped. signal	3.9	–73%	23.4	–66%
		PHB	1.3	–91%	7.0	–90%
Distal	Two stage	Ped. signal	2.8	–80%	5.9	–91%
		PHB	1.2	–92%	0.0*	–100%

* This scenario actually resulted in a net decrease of the total roundabout delay, explained by the fact that the signal was metering demand on a busy approach. Number was limited to a positive range for this table.

reduced that delay by 56% and 42% to 6.3 s and 39.4 s, respectively. The use of a two-stage phasing at the same proximal location resulted in delay reductions of 71% and 64% over the base case even if a regular pedestrian signal was used. The PHB resulted in further delay benefits and reductions of 89% and 92% over the base case.

Modified crossing geometries such as a zigzag or distal crosswalk resulted in similar delay savings for both a regular pedestrian signal and the PHB phasing scheme. In all cases the PHB resulted in additional delay savings. The modified exit leg geometry for the zigzag and distal crosswalk locations can further reduce spillback potential into the circulating lane due to added vehicle storage at the roundabout exit lane. The detailed analysis results in Appendix L discuss the average and maximum vehicle queues at the crosswalk in light of the available queue storage.

The analysis further suggested a non-monotonic relationship between the treatment effects and the levels of vehicle volumes. Pedestrian-induced vehicle delays appeared to be greatest as traffic volumes approached roundabout capacity. The need for innovation in pedestrian signal application is therefore less pronounced at low traffic volumes but should be a key consideration at busy roundabout junctions. As vehicle volumes increase, pedestrian signals become even more important from an accessibility perspective. The most promising approach for minimizing the impacts on vehicular traffic while ensuring access for blind pedestrians appears to be a strategic reduction of the vehicle red indication. The authors showed that this can be achieved by shortening the crossing distance through a two-stage crossing or through the introduction of a "Flashing Red" phase in a PHB phasing scheme.

A sensitivity analysis of the effect of increasing pedestrian volumes supported the hypothesis that vehicle and pedestrian delay impacts increase at a diminishing rate as signal operations approach the limit of *maximum number of actuations per hour.* Pedestrian and vehicular delays generally appear to plateau at volumes in excess of 200 pedestrians/hour. This suggests an application for signalization as a means of controlling pedestrian interference to vehicular operations—an interesting twist to the existing pedestrian signal warrant that evaluates only the available crossing opportunities for pedestrians within a given time interval. Clearly, this assumes perfect pedestrian compliance with the signal phasing.

Discussion

This chapter has discussed two extensions of the NCHRP Project 3-78A field results for application to other locations, geometries, and traffic volumes. The first part of this chapter presented empirically derived mixed-priority pedestrian delay models that can be used to estimate pedestrian delay at single-lane roundabouts, two-lane roundabouts, and CTLs. The explanatory variables in these delay models are consistent with the four behavioral probability parameters defined in Chapter 4 and used in the Chapter 5 evaluation of field results. The second part presented the concept of using these four probability terms in a microsimulation environment for further extension analysis. Microsimulation tools have the advantage that the analyst can readily explore the impacts of different geometries, traffic volumes, and pedestrian and driver behavior on selected performance measures.

The constraint of both approaches is their limited applicability to measures of pedestrian safety. The chapter briefly touched on the ability to extract surrogate safety measures from simulation in the form of pedestrian–vehicle conflicts or near collisions. This approach is the focus of an ongoing national effort by FHWA but has yet to be extensively validated. This research has demonstrated that it is possible to extract pedestrian–vehicle conflict data from simulation and further that the rate of conflicts is responsive to changes in the four underlying probability parameters. Presumably, changes in these parameters represent the implicit impacts of pedestrian crossing treatments. However, while there is confidence in the delay measures resulting from such analysis, the risk measures are at this point strictly theoretical.

The concept of predicting pedestrian–vehicle conflicts from simulation requires extensive field validation to build confidence in the approach. While this research recorded a field measure of risk in the form of O&M interventions, its occurrence and variability across participants makes it challenging to perform such validation. Further, while some of the tested treatments showed a significant impact on these O&M interventions, additional observations are needed to validate a simulation-based safety performance assessment.

CHAPTER 7

Interpretation and Application

This chapter presents an interpretation of the findings of research performed under NCHRP Project 3-78A in the context of application to engineering practice. The chapter initially presents a synthesis of the study approach, followed by a summary of the field studies performed during this project. It then discusses specific implications for facility design and accessibility considerations at the three tested facility types: channelized turn lanes, single-lane roundabouts, and two-lane roundabouts. The chapter concludes with a discussion of future research needs and recommendations for follow-up work to this project.

Synthesis of Approach

The results of NCHRP Project 3-78A have three principal components: (1) the formulation of a framework for describing accessibility, (2) field study results of blind pedestrian crossing studies including treatment installation, and (3) approaches for extension of the findings to other locations.

First, the project devised an analysis framework for assessing the accessibility and usability of different crossings to pedestrians who are blind. While the framework was developed in this project in light of specific challenges to this group of pedestrians, it has broader application to other pedestrian populations. The accessibility framework quantifies the crossing performance at a tested location in four dimensions:

1. **Crossing opportunity criterion**
   – Are there sufficient crossing opportunities in the form of yields or crossable gaps?
2. **Opportunity utilization criterion**
   – Are the crossing opportunities 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?

This framework allows the analyst to isolate different components of the crossing task at crosswalks. Any treatments intended to improve the accessibility are specifically targeted to one or more of the criteria. On the basis of these four analysis dimensions, the report describes the development and implementation of a set of performance measures. The performance measures include the probability of encountering crossable gaps, P(CG_ENC), and yields, P(Y_ENC), and the probability of utilizing these crossing opportunities, $P(GO|CG)$ and $P(GO|Y)$. These performance measures were used in field studies to quantify the first two accessibility criteria. The performance measures are further hypothesized to affect criteria 3 and 4, the delay and safety experienced by the pedestrian during the crossing. Chapter 4 of this report provides detailed descriptions and definitions of all performance measures. The present research effort serves to introduce a structured and measurable framework for quantifying the principal operational parameters of accessibility.

Second, the research conducted a total of 11 field studies at multiple test locations involving crossing trials of blind study participants. These included four studies at an intersection with CTLs, two of which were posttests after installing sound strips, lane delineators, and a pedestrian-actuated flashing beacon (one location only). Four studies were performed at two-lane roundabout crosswalks. Again, two were posttests after installing a raised crosswalk and a pedestrian hybrid beacon at the two studied crosswalks. The remaining three studies were performed at two single-lane roundabouts. One of the single-lane roundabouts was evaluated in a pretest and posttest design, but without treatment installation, to test for a learning effect in study participants with repeated exposure. A twelfth dataset, originally collected for a prior research effort, was also included in the analysis. This dataset was also for a single-lane roundabout. In total the field studies evaluated approximately 3,300 individual crossing attempts by 56 different blind study participants in 12 studies at five different sites.

In the studies, pedestrians who were blind repeatedly crossed the street at roundabouts and CTLs. The participants were at all times accompanied by a certified O&M specialist who was trained to prevent collisions by intervening in the crossing attempt in the event that participants misjudged traffic patterns. The data these studies yielded were very complex. A multitude of factors were observed and recorded both in the field in real-time and in post-processing from video recordings. Details on the study methodology are given in Chapter 3. The data analysis involved formulation of a new analysis framework for quantitatively describing pedestrian accessibility that is described in Chapter 4. Detailed results are presented in Chapter 5 with supplemental results given in Appendix A.

Third, the research presented two approaches for extension of the analysis framework and the field study results to other locations and traffic patterns (Chapter 6). Using the pedestrian and driver behavioral attributes defined in the analysis framework, the team developed regression-based mixed-priority models to predict pedestrian delay at unsignalized crosswalks. The term "mixed-priority" refers to a crossing situation where some pedestrians cross in gaps between moving vehicles while others cross in front of yielding vehicles. The models are sensitive to the fact that there is variability in the rates of occurrence of gaps and yields as well as in the rates of utilizing these opportunities. Separate delay models were developed for each of the three facility types, and guidance was provided on how the models may be applied to other sites. The extension piece further provided guidance for how microsimulation models can be used to analyze pedestrian–vehicle interaction at roundabouts and channelized turn lanes. The discussion demonstrated that the analysis framework is compatible with a simulation environment. Special attention was given to a sensitivity analysis of different pedestrian signalization options at single-lane and two-lane roundabouts.

Modeling was not done with regard to the safety of pedestrians who are blind. The direct measure of safety used in this research (O&M interventions) was not frequent enough to support modeling. Nonetheless, interventions were numerous, representing times where there was a high likelihood of the blind pedestrian being injured or killed without evasive action on the part of a driver or the pedestrian. In the worst test condition (CTL pretest), the probability of intervention was 1 in 18. Viewing this statistic from the perspective of a blind traveler who commuted across that CTL, this level of risk is unacceptable. Intervention rates were also high at other sites, including the two-lane roundabout at pretest and one of the single-lane roundabouts. Consequently, the delay modeling effort should only be interpreted as one piece of guidance in the broader question of accessibility of a site.

Implications of Field Study Results

There are many challenges inherent in translating accessibility research into policy guidance. Roundabouts and CTLs, along with the individuals who use them, are diverse. The facilities differ in terms of vehicle volume, level of ambient noise, driver culture, and physical design. The individuals who participated in the NCHRP Project 3-78A studies differed in their propensity for risk taking, hearing ability, travel experience, and physical and cognitive abilities. It was a challenge in this project to draw appropriate, general conclusions from the results from a program of research that was limited in comparison to the range of factors that might influence street crossing. The program was limited by resources and by the availability of adequate numbers of participants near roundabout and CTL facilities. Because of these factors, the team narrowed the focus by studying relatively skilled, functionally blind individuals and by evaluating only two treatments at roundabouts (PHB and raised crosswalk) and two at CTLs (sound strips and flashing beacon). Other limitations in the work included the fact that sample sizes were modest and participants were recruited rather than selected randomly from a population.

Despite the limitations noted above, the team derived conclusions from the studies where possible. Given that there are numerous explanations for the results obtained, the team also hypothesized about the possible explanations or interpretations of the findings. The information that follows is organized by type of facility (CTL, single-lane roundabout, and two-lane roundabout).

In regard to the CTL, the studies showed high rates of intervention at pretest for both CTLs (9.4% and 5.6%, respectively). Since the pretests at the two locations were completed by the same participants on the same day, and no treatment was in place, it is likely that the differences observed in the two locations in regard to intervention rate are due to ambient noise levels or vehicle speeds and volumes. Traffic counts were higher at the SS-ONLY installation, which was the CTL with the higher intervention rate. Regardless of the cause, intervention rates at both CTL locations were very high and represent an unacceptable level of risk for the participants. The pretest at the two CTLs further showed high average delay per subject at 26.2 s and 23.4 s, respectively, to cross a single lane of traffic. However, individual delays were much higher, and some trials even timed out after participants were not able to cross within 2 min.

The posttest data revealed that both tested treatments yielded a significant reduction in intervention rates and reduced average delay to some extent. The combination of sound strips and flashing beacons reduced the intervention rate and delay more than the sound strips alone, although the difference between the two posttest intervention rates is not statistically significant (p = 0.3483). However, the team concluded that even the lower intervention rate (1.4%) was still unacceptably high and that additional treatments are needed at this CTL to achieve an acceptable level of crossing safety.

The research team did not evaluate any treatments at single-lane roundabouts. This research conducted pretests at a single-lane roundabout in Charlotte, NC, and Golden, CO. Also included in this report are findings from a study conducted at a single-lane roundabout in Raleigh, NC. The team did not pursue treatment installation as originally planned at the Charlotte single-lane roundabout, partly because it was believed that the treatment would be unlikely to result in a measurable effect of pedestrian safety, based on an intervention assessment. The pretest intervention rate was low, at 0.8%, so there was not much room for improvement from a safety perspective. It was therefore concluded that project resources would be better spent elsewhere.

However, at this particular single-lane roundabout, participants experienced relatively long pedestrian delay, probably due to the very low yielding rate by drivers and the tendency of participants to wait for long gaps before initiating crossing rather than forcing yields. The fact that interventions were relatively low at the Charlotte location led the team to believe that acoustic conditions at this intersection facilitated the use of a gap detection strategy, that participants recognized this fact and used this strategy, and that the use of this strategy, while resulting in delay, yielded an acceptable level of risk. It is concluded that a treatment is not necessary at this roundabout under prevailing traffic conditions when crossed by blind pedestrians who report they cross streets independently. It is unclear if and how behavior and performance measures at this site would change with higher traffic volumes and fewer (large) gaps.

In regard to the Golden single-lane roundabout, there was not a statistically significant difference between the intervention rate at pretest (1.4% of crossings) and posttest (0.5%). Both studies further showed a relatively low average delay for participants of 11.9 s and 12.1 s, respectively. No treatment was installed at the single-lane roundabout, and the same participants participated in both rounds. The decision for two studies without treatment installation was motivated by the goal to test for a learning effect in participants with repeated (twice) exposure to the same site and the same study protocol. The same participants who crossed at this site also crossed at the studied two-lane roundabouts to allow for a direct within-participant comparison of a single-lane and a two-lane roundabout. The fact that no learning effect was evident at the single-lane roundabout from a safety or delay perspective gives confidence that any pretest–posttest difference at the two-lane roundabout can in fact be attributed to a treatment effect. The team concludes that the Golden single-lane roundabout did not pose extraordinary crossing challenges under prevailing traffic conditions, but some risk remains. Similar to the Golden site, it is unclear if and how behavior and performance measures would change under different traffic conditions.

The Raleigh single-lane roundabout data was collected as part of an earlier research effort, and the data was reanalyzed using the analysis framework developed as part of this project. The intervention rate was the highest of all roundabouts studied (although the rate was lower than the rate at the CTL site studied). The team considers the 3.9% intervention rate at this intersection to be unacceptable and suggests that a treatment is needed at this intersection to reduce crossing risk. It needs to be noted that this prior study actually included some participants with normal vision and that these sighted participants did not experience any interventions. It is unclear what factors contributed to the high rate of interventions for participants who were blind at this location. There was a relatively high proportion of yielding vehicles, and it may be that participants crossed in what they perceived as a gap but what was actually a yield that was not detected by the blind pedestrian. Individuals may have initiated crossing at the same time a yielded vehicle began to move. In this scenario, the O&M specialist would likely have intervened. Anecdotal observations seem to support this conclusion.

At the Golden two-lane roundabout, the intervention rate dropped from 2.8% and 2.4% of trials prior to installation of treatments (for the raised crosswalk and the pedestrian hybrid beacon, respectively) to zero after installation of treatments. The RCW treatment reduced average pedestrian delay from 17.0 s to 8.0 s. The PHB reduced delay from 16.0 s to 5.8 s on average for crossing two lanes of traffic. The team concludes that without treatment in place, pedestrians who are blind and who cross the street are exposed to an unacceptable level of risk. It is further concluded that the risk level appeared acceptable after either of the tested treatments was installed at this site and under prevailing traffic conditions. It is unclear if and how crossing performance would change with higher traffic volumes or at a site with different geometry.

The team was surprised that the intervention rate for *both* treatments was zero, as it was anticipated that the raised crosswalk would not yield as great a risk reduction as the PHB. Field notes from a team observer indicate that there were eight risky multiple threat crossings at the raised crosswalk that did not actually result in interventions. No such events were recorded at the PHB. Additional research at other locations and with other individuals is necessary to determine whether there is in fact no difference in risk between these two treatments.

To summarize, the key observations from the field studies were:

- That it is possible to apply the analysis framework to field studies and to describe pedestrian crossing performance in measurable terms consistent with the traffic engineer's understanding of general traffic performance. The analysis framework is sensitive to differences between sites and the impact of pedestrian crossing treatments.

- That a measurable concept of accessibility can be quantified in terms of the availability and utilization of crossing opportunities in the form of gaps and yields and that these measures can be used to describe the performance measure of delay, although delay is not a measure that can, by itself, be used to measure accessibility to blind pedestrians.
- That significant variability across study participants was observed for all sites, highlighting individual differences in terms of travel skills, decision-making, and level of crossing comfort. Significant differences also exist across different test sites, including the three tested single-lane roundabouts.
- That some CTL crossings are more hazardous than single-lane or two-lane roundabouts for pedestrians who are blind, and that the tested CTL treatments—sound strips and pedestrian-actuated flashing beacons—did not effectively alleviate all accessibility concerns. The sound-strip treatment did show potential, and modified materials and installations should be explored further, in addition to other potential modifications at CTLs that reduce vehicle speed and increase yielding. A major concern is the ability of pedestrians to detect yielding vehicles in the high ambient noise environment of most CTLs. Treatments such as sound strips, lane delineators, and pedestrian-actuated flashing beacons cannot be expected to provide adequate accessibility at two-lane CTLs.
- That the three single-lane roundabouts varied considerably in the availability and usability of crossing opportunities, delay, and risk for pedestrians. At least one tested single-lane roundabout (PS-RAL) showed a relatively high incidence of interventions (3.9% mean, 15.6% for one individual), and another (DAV-CLT) had relatively high pedestrian delays (25.3 s mean, 74.0 s maximum individual average). Therefore, while for one single-lane roundabout crossing and some blind pedestrians no treatments appear necessary under tested conditions, at least one high-risk and one high-delay crossing warrant further treatment evaluations.
- That both tested two-lane roundabout treatments, raised crosswalk and pedestrian hybrid beacon, appeared to significantly enhance the accessibility at the tested site. The improvements were evident in the form of significantly reduced pedestrian delays and no posttest interventions with either of the treatments. However, field observations by a trained observer noted more potentially risky events at the raised crosswalk and none at the PHB, suggesting that the latter treatment represents the safest (tested) crossing condition for blind pedestrians at this site.

The present studies suggest that the accessibility of a site is a function of the conflicting traffic volume, the speed of traffic, the ambient noise, the level of driver courtesy toward pedestrians, and probably other variables yet to be identified and studied. A range of treatments is available and discussed in Chapter 2 that have the potential of influencing one of more of the dimensions of accessibility defined in the framework outlined in Chapter 4.

Policy Implications

While the U.S. Access Board draft PROWAG specifies a pedestrian-actuated signal at two-lane roundabout crosswalks with pedestrian facilities, the ADA allows equivalent facilitation in all implementations of requirements. Consequently, other treatments that provide equivalent accessibility are acceptable. This is to allow for improvements in technology, developments in materials or research, or the implementation of new ideas and information. It is up to the designer and/or constructing jurisdiction to provide justification for installation decisions in the case of an ADA complaint. The team believes that there is some confusion in the interpretation of these standards in that some may fail to recognize the inherent difference in civil rights laws and engineering standards. While the current draft requirements focus on two-lane crossings at roundabouts and CTLs, as well as treatments that provide information about the crosswalk location such as landscaping or barriers, there is still a responsibility to design and build ***all*** facilities to be "accessible to and usable by" pedestrians with disabilities (DOJ 1990).

An increasing national debate in this area is very positive. However, a narrow focus in that debate on the signalization of two-lane crossings is associated with two major concerns: (1) by focusing on two-lane roundabouts, the accessibility of single-lane approaches is being largely ignored, and (2) the emphasis on signalization gives a perceived blanket obligation for a one-size-fits-all treatment at all two-lane locations, regardless of the site specific geometry, traffic volumes, and driver behavioral patterns.

There is no real debate over the fact that well-designed modern roundabouts are generally safer for vehicular traffic than many traditional intersections they replace. There is further no real debate that many sighted pedestrians can safely negotiate single-lane roundabouts and most two-lane roundabouts. However, research to date is unclear about the ability of other pedestrian populations, including elderly pedestrians, children, and those with mobility impairments, to cross safely at these locations. Further, it is unclear what challenges are posed by newly emerging three-lane roundabout designs with potentially high design speeds and high traffic volumes.

The data presented in the present work strongly argues against the belief that all single-lane roundabouts are created equally. While one of the studied sites showed generally low delay and risk, a second site had high pedestrian risk, while the third exhibited high delays. There was high inter-participant variability that emphasizes differences among individual blind travelers.

Another important finding was the difficulty and level of risk encountered by blind pedestrians when attempting to cross a relatively high-speed, high-volume CTL. A sound-strip treatment did not prove to be effective in reducing risk, partly due to the high noise levels and difficulty of auditory detection in noise, and partly due to the lower sound output of the sound strips when vehicles were moving slowly over them. A pedestrian-actuated beacon with an audible message improved yielding behavior somewhat, but the posttest crossing performance was still associated with a high rate of O&M interventions. Consequently, the accessibility of this CTL site was not established with the treatments tested. Attention needs to be given to this access issue in addition to the attention to accessibility of roundabout crossings.

In general, these studies have shown that the tested treatments can, in fact, change the behavior of drivers as well as pedestrians and that these changes can be measured and quantified. The treatments differed in their effect on drivers and on pedestrians who are blind, and represent various degrees of installation cost and impact to the driver and pedestrian populations. The results and conclusions previously discussed should not be construed as absolute, and readers should remain cautious about basing policy decisions on these limited data. This report provides a firm conceptual measurement-driven approach to the study of the effect of such treatments, but it is clear that more field research is needed to explore and substantiate treatment effects.

Discussion

In the following, the team offers some additional discussion to highlight various aspects of the field study results. The section will highlight specific aspects of the study results that are important in guiding the decision-maker in evaluating the level of accessibility of a given crosswalk to pedestrians who are blind and who are relatively experienced travelers.

Single-Lane Versus Two-Lane Approaches

A pedestrian crossing with two conflicting lanes is generally more challenging than one with a single lane because the vehicle state in both lanes affects the decision-making. Visual obstruction and auditory masking of vehicles in the near lane may block activity in the far lane, which may result in *multiple-threat* situations (Zegeer et al. 2002).

The experiments at the Golden two-lane roundabout showed that pedestrians who are blind are often capable of utilizing *dual crossing opportunities* at this location, characterized by a yield or crossable gap in both lanes. However, the analysis showed that the rate of occurrence of these types of opportunities can be low, resulting in high pedestrian delays. The occurrence of dual crossing opportunities is expected to be even less at approaches with higher conflicting volumes and speeds. In addition to delay, participants experienced a significant amount of risk, as indicated by the frequency of O&M interventions. Both delay and risk were reduced with the installation of each of the two tested treatments (PHB and RCW), thereby improving the accessibility and usability of the site. Before treatment installation, the same participants experienced higher delay and greater risk at the two-lane crossings compared to the single-lane roundabout. After treatment installation, the crossing performance at the two-lane approaches improved to levels comparable to the tested single-lane roundabout crossings without treatments. However, some safety concerns remained at the RCW, evident by other risky events (that did not result in interventions) that were noted by a trained observer recording data during the studies.

While some of the tested single-lane approaches seemed more easily crossable than an untreated two-lane approach, some exceptions need to be highlighted. In particular, the high-speed, high-volume, single-lane CTL crossings resulted in very high delays and the highest risk for any of the test sites. Also, the Raleigh roundabout had high intervention rates despite lower speeds and generally courteous driver behavior. Consequently, even a single-lane crossing can be challenging and potentially dangerous to cross if traffic volumes, vehicle speeds, and driver behavior are not conducive to crossings by pedestrians who are blind.

The Impact of Vehicle Speed

High vehicle speeds have been linked to a decreased likelihood of driver yielding (Geruschat and Hassan 2005) and are further associated with an increased pedestrian injury rate when collisions occur. In the context of pedestrian crossings at roundabouts and CTLs, a “high speed” is categorized as a design speed or average observed speed at the crosswalk greater than 20 mph.

In this research, the high-speed channelized right turn lanes resulted in the greatest pedestrian delay and risk, supporting the hypothesis that pedestrian accessibility is tied to vehicle speeds. The treatment effect of the RCW at the two-lane roundabout provides further evidence for this. The RCW significantly reduced pedestrian delay and reduced risk while not being associated with any form of red signal display like the pedestrian hybrid beacon. After RCW treatment installation, only a small percentage of drivers passed in front of the waiting pedestrian without yielding at the tested location. The findings on vehicle speed have two primary implications for practitioners:

First, while the tested single-lane roundabouts were found to be manageable by most pedestrians who are blind, it is expected that a higher-speed design will have a severe adverse effect on accessibility. Following the same argument, larger two-lane roundabouts with higher design speeds and two or more lanes can be expected to be less accessible than the tested two-lane roundabout in Golden.

Second, if an existing site features high speeds through a combination of roadway geometry and driver behavior, it is hypothesized that a higher-impact treatment would be needed to make the site accessible. Low-impact treatments like the ones tested at the high-speed CTL location are apparently not sufficient to make a high-speed crossing accessible. It is hypothesized that a traffic calming treatment like the raised crosswalk or a red signal display would be more appropriate at high-speed locations. However, more research on these treatments is necessary to solidify this claim, mainly due to the observed multiple threat incidents at the RCW in the posttest.

Crossing Geometry

In all crossings observed in this research, vehicles approached from only one direction at a time. Both roundabouts and channelized turn lanes feature splitter islands that provide the benefit of refuge for pedestrians before they complete the second part of the crossing. It is important to emphasize that this form of traffic pattern is a potential benefit of both types of intersection compared to intersections with one-stage crossings across two-way traffic.

Despite the advantages of one-way approaching traffic, identifying gaps and yields with curved vehicle trajectories and elevated levels of ambient and vehicular noise contribute to crossing challenges at these types of crosswalks for pedestrians who are blind. In particular, prior research (e.g., Ashmead et al. 2005, Guth et al. 2005) has noted that the exit portion of a roundabout crossing is more difficult to cross due to difficulties discerning exiting traffic from circulating traffic and also due to less frequent yielding behavior. From a driver behavioral perspective, pedestrians may be considered more of a nuisance when exiting the roundabout. Upon entering a roundabout, vehicle trajectories are characterized by deceleration (to be able to safely navigate the circle) and the potential to have to come to a stop (to yield to traffic in the circulating lane). On the contrary, the exiting driver accelerates and psychologically has cleared the delay-causing intersection.

In this research, the hypothesized difference between entering and exiting traffic was evident in a lower likelihood of driver yielding at the exit. Interestingly, this difference did not result in a consistent and notable increase in delay or safety at the exit portion of the crosswalk across sites.

Another aspect of crossing geometry is the relative placement of the crosswalk in relation to the roundabout or the channelized turn lane. At both types of facilities, crosswalks are typically located at least one vehicle length away from the circulating (downstream) lane to ensure (1) storage for one vehicle downstream of the crosswalk and (2) a separation between the driver's cognitive tasks of interacting with pedestrians and the circulating traffic (or downstream CTL traffic). However, this placement of the crosswalk often results in vehicle queues across the crosswalk. Some interventions (especially at the CTL) occurred in response to vehicles in queues that began moving as the blind pedestrian approached the side of the vehicle, not realizing it was there. While this research did not perform any field studies on alternative crosswalk locations, a simulation-based analysis of roundabout signals demonstrated advantages in vehicular delay of the zigzag or distal crosswalk location. The greater exit-lane separation enhanced these two objectives (more storage and better separation of cognitive tasks for the driver), but is associated with two tradeoffs that may negatively affect pedestrians: (1) with increasing separation, the speed-reducing effect of the roundabout is reduced, and (2) the pedestrian travel distance is increased if measured from the main intersection. However, it is unclear at this point whether an alternate crosswalk geometry has any (positive or negative) impact on the crossing ability of pedestrians who are blind.

Inter-Participant Variability

The analysis results showed a very large variability between different blind participants. It needs to be emphasized that at all of the crossings, there were some individuals who were able to cross with a reasonable amount of delay and without experiencing any interventions. Others experienced multiple interventions at the same crossing, and others had some trials that were terminated because a 2-min time-out limit was reached. Appendix A provides more detail on the inter-participant variability and shows the distribution of key performance measures across participants. This variability causes challenges for the analysis, the interpretation of the results, and ultimately the decision to consider a site accessible with or without treatment.

The results in this report emphasize average performance and associated variability (i.e., standard deviation) when evaluating pretest–posttest treatment effects. Consequently, any differences that are statistically significant are to be considered noteworthy in light of high standard deviations. For example, the two-lane roundabout treatments seemed to have improved crossing effectiveness and safety for all participants to the point of reducing delay and eliminating interventions (at the given sample size). On the other hand, the CTL treatments did not help all participants and left many with significant challenges in crossing at the location. The inter-participant variability also means that sites that may be accessible for some travelers pose severe challenges for others. For example, some participants readily crossed at the DAV-CLT single-lane roundabout while others experienced over 80 s of average delay.

Also coming into play was the situation behind the lead vehicle. If there was no vehicle following the lead vehicle so closely that there was a high chance of a collision, the O&M specialist often did not intervene. Participants apparently were often unaware that a vehicle was approaching. Also, many participants crossed when a vehicle had yielded for them but they did not realize that a vehicle had yielded until it accelerated across the crosswalk after they had crossed. In short, while the frequency of interventions was relatively low, conversations with participants after trials and after the study led the team to believe that the participants often were unaware of the situation when they crossed the street.

Some variability in performance may have been due to participant behavior. The team presumes that some behaviors result in lower risk crossings than others, but the team did not manipulate participant behavior and did not explicitly study it. Some participants stood very upright and still while listening and waiting to cross, with their canes held vertically in front of their bodies, while others leaned forward as they anticipated crossing or took a step forward and extended their canes. Some turned their heads toward the traffic (and may have been perceived as looking at traffic) and others looked down while listening. These various postures appeared to the research team to affect yielding behavior and crossing behavior. A lack of training on roundabout crossings also may have allowed participants to use less than optimal techniques.

The same general points made above for roundabouts appear to be true for CTLs. Many of the blind participants did not understand the layout of the CTL before the familiarization provided as part of the study. For example, they were unaware of the potential crosswalk locations, the shape of the island, and the addition of a deceleration lane at the intersection, and many were confused about the fact that the signal did not also control the right turn lane. Pedestrians who are blind may also benefit from instruction that helps them better understand the geometry and traffic flow at CTLs and various crossing strategies. It is hypothesized that even with intense and repeated O&M training, many of the crossing challenges at busy and high-speed crossings cannot be alleviated. Accordingly, additional infrastructure-based treatments as tested in this research are needed to satisfy concerns of pedestrian accessibility.

Learning Effect and O&M Training

The inter-participant variability raises the question of whether individual travel skills can be improved through training and education, to the point where they represent a viable treatment to enhancing accessibility. This form of training is the basis of the field of orientation and mobility, which goes well beyond the scope of this report. All participants in this research were familiarized with the test location by walking the perimeter of the site, by exploring the geometry through use of a tactile map, and by performing some (assisted) practice crossings prior to starting the actual experiment.

During orientation to the study, participants did not receive any instruction in making crossing decisions. This lack of instruction from the O&M specialist was part of the research protocol, and participants were told that instruction or feedback would not be provided. However, it may have resulted in some participants assuming that they were making good decisions about crossings if interventions did not occur, when in fact the O&M specialist recognized that the situation was potentially risky but did not intervene because she knew that the approaching vehicle could (and was) taking evasive action (usually braking or accelerating to pass the crosswalk before the pedestrian arrived in the case of the two-lane roundabout). Also, some participants stepped out at times that forced a yield, apparently without realizing they were doing so. In this situation the O&M specialist did not intervene if she was confident that the vehicle was yielding and would stop in time, even in situations of relatively fast vehicle deceleration.

In this research, the single-lane roundabout in Golden provides insights into the effect of added exposure or experience on crossing. Since no treatments were installed at the site, the pretest–posttest comparison represents a control for any learning effect that may have affected the concurrent Golden two-lane roundabout study. Since no such effect was measured, two conclusions can be drawn. First, the pretest–posttest improvements in crossing performance at the two-lane roundabout are likely attributable to a treatment effect and not a learning effect. Second, the repeated exposure (twice) of participants to the same single-lane roundabout did not significantly improve their crossing performance.

While anecdotal evidence suggests that participants were more comfortable in the second round of exposure (the posttest), their earlier experience at the roundabout was not O&M training or instruction, which might be beneficial, particularly at single-lane roundabouts.

It's possible that O&M instruction may have a more significant and permanent effect. There is clearly a need for education of pedestrians who are blind or visually impaired about roundabouts, including how to make safe crossings. Just as little is known about the most appropriate engineering treatments for promoting the accessibility of roundabouts, little is known about the most appropriate crossing strategies for blind pedestrians. As illustrated by this project, the engineering profession and the O&M profession must work together to promote accessibility. It is therefore essential that engineering professionals have a general understanding of the O&M profession, and vice versa. What follows are some general principles of O&M instruction to help promote this mutual understanding.

First, it is important to understand that people who are blind rarely receive training for every route that they travel or at every intersection they cross. O&M instruction is similar to driver education; people may receive individualized on-the-street training, but they typically receive such extensive training just once and then generalize to new areas and update their skills as they travel and encounter new situations. For individuals who have been blind for many years, formal O&M instruction may have been received decades ago. Depending on an individual's travel experience and capacity for self-instruction, he or she will be more or less knowledgeable about developments in traffic engineering and their implications for non-visual travel. Just as there is often a need for an educational campaign for drivers about how to manage roundabouts when roundabouts are new in an area, there may be a need for an educational campaign for pedestrians who are blind or visually impaired when roundabouts are installed.

Second, O&M instruction is usually not amenable to classroom instruction, written material, or website content. Most O&M instruction is provided "on the street" to ensure that a blind pedestrian can experience and practice a new set of skills. At roundabouts, this would involve actual experience with roundabout layout and crossings, along with instruction by a certified O&M specialist. In addition to providing the initial instruction and structured experience, the O&M specialist is present to reduce risk (including intervening) and to provide feedback during the initial stages of learning. The initial instruction may involve the use of tactile (raised line) maps of the roundabout. But it is essential to (eventually) experience roundabouts—for example, by walking around and through them and listening to traffic. Ideally, as with signalized intersections, this instruction would begin with relatively simple roundabouts and progress to more complex ones. Most of the general concepts to be mastered by the blind pedestrians are the same as those for sighted pedestrians, including, for example, intersection and crosswalk geometry, traffic movements, and crossing strategies. Other concepts have greater relevance to blind pedestrians, such as the 3 to 4 s of sound masking created by a vehicle that has just passed the crosswalk in front of (or in back of) a pedestrian. Knowledge of these concepts would then be followed up with practice, feedback, and more practice. As noted above, the most appropriate treatments and strategies for non-visual roundabout crossing remain an open question, and this project has been a start toward developing such treatments and strategies.

As a final caveat on this topic, it is important to note that this project has focused on pedestrians who are blind, not pedestrians with low vision. Related research (e.g., Geruschat et al. 2006; Hassan, Geruschat, and Turano 2005) has identified challenges experienced by pedestrians with low vision that are not experienced by pedestrians with normal vision.

Confidence in Decision-Making

In Chapter 4, the term "utilization" was used to describe a pedestrian crossing in a yield or gap. This term objectively describes observable behavior rather than making presumptions about the pedestrian's ability to detect a yield or crossable gap. In fact, through the experimental trials in this research it became evident that some blind travelers may well be aware of the presence of, for example, a yielding vehicle (i.e., detection), but may be reluctant for one reason or another to utilize the crossing opportunity. The individual's rationale for non-utilization may be tied to past experience (a driver who yielded but then changed his or her mind), uncertainty (about whether the vehicle is yielding to the pedestrian or for another reason), or ultimately a lack of confidence in the viability and accuracy of the detection.

Sighted pedestrians have the advantage over blind pedestrians in being able to judge gaps and detect yielding vehicles using both visual and auditory information. Lack of access to visual information places the blind pedestrian at a distinct disadvantage. The distance at which single vehicles can be detected is shorter, perception of direction from which single vehicles are coming is less precise, perception of vehicle trajectory is very difficult on curving paths, perception of rate of approach (hence time-to-contact) is less precise, the sound of a vehicle that has just passed the crosswalk can mask the sound of an approaching vehicle, and it is often difficult to detect the presence of a yielding vehicle. The presence of multiple vehicles exacerbates all these difficulties. As a consequence of these difficulties, pedestrians who are blind typically delay crossing longer than pedestrians who are not. This may result in vehicular queuing. It may also result in a yielding driver accelerating at precisely the time the pedestrian who is blind decides to begin to cross. This type of behavior was observed during this research. Sighted pedestrians also have the advantage in that they can attempt to force yields given the ability to establish non-verbal (visual) communication with the approaching driver(s). Blind pedestrians lack that advantage.

From observations, the confidence of pedestrians to make crossing decisions is related to their personal travel skills, experience, and willingness to accept risk. It may further be (partially) influenced by the opportunities presented, where the crossing strategy is a function of traffic patterns during the study. Under low-volume conditions, participants can reasonably expect that a large gap is likely to occur and may therefore be more inclined to reject shorter gaps or yields. It is likely that varying degrees of confidence contributed to the observed inter-participant variability described above. In other words, the difference between participants may be a combination of skill (e.g., hearing ability, cognitive ability) and confidence. It is presumed that confidence in decision-making may be improved with repeated exposure and training.

However, the analysis also suggests that pedestrian confidence was increased with some of the crossing treatments, even where an effect was not hypothesized. Most notably, the installation of the raised crosswalk and flashing beacon treatments resulted in an increase in the rates of opportunity utilization, $P(GO|Y)$ and $P(GO|CG)$. At the same time, the two-lane roundabout RCW treatment also contributed to an increase in the number of forced yields, defined as the pedestrian stepping into the roadway before a yield was initiated by the driver. A similar increase in the willingness of sighted pedestrians to accept risk was observed in a field study of two different pedestrian crossing treatments (Schroeder 2008). In observational before-and-after studies with in-road pedestrian warning signs and in-pavement pedestrian-actuated flashing beacons, the author noted a decrease in pedestrian critical gap after treatment installation. It was hypothesized that pedestrians felt "empowered" or at least more noticeable with the treatment in place, which effectively lowered their perceived risk threshold.

These trends raise the question of whether the apparent increase in confidence is desirable. Clearly, more forced yields would be a concern if the driver had not paid attention. On the other hand, even with higher opportunity utilization and more forced yields, the rate of interventions decreased.

Self-Assessment of Risk and Travel Skills

The apparent increase in confidence is also reflected in the post-experiment participant questionnaires, where participants responded positively to a question regarding their confidence in crossing safely, both in the pretest and posttest, and to the treatments. Across all settings, participants' ratings of confidence in crossing safely, both before and after treatments, were quite high (a range of 3.66 to 4.83 on a scale of 1, low confidence to 5, high confidence). However, the range of interventions across all sites and with or without treatment was also large, from 0.5% to 9.4%. This raises questions about the relationship between (stated) confidence in decision-making and the quality of these decisions.

It is quite likely that participants often failed to recognize when they made risky crossings. On many crossings, participants may have been unaware of the extraordinary avoidance maneuvers of drivers, or of how close they came to a crash. The O&M specialist gave participants no feedback regarding crossings, many of which were quite risky but nonetheless did not result in interventions because the O&M specialist could see that drivers were taking avoidance action. There is a large body of research indicating that people tend to underestimate the likelihood that they will be involved in an adverse event, reviewed in Greening and Chandler (1997). In the typical paradigm for this research, participants are told the average rate of occurrence of a given adverse event, such as a crash, and are then asked to estimate the likelihood of their being involved in a crash. Especially when participants have control over behavior that could result in an adverse event (as they did in the present research), they are likely to underestimate their risk of being involved in the adverse event. They believe that they are better than average at the skills necessary to avoid the adverse event. The high confidence ratings in the present research, despite the relatively high risk, could be an example of this phenomenon that has been documented for individuals having unimpaired vision.

Perhaps even more to the point, estimates of cumulative risk have been found to be especially skewed toward overestimation of safety (Knauper et al. 2005). Thus an individual who actually required experimenter intervention on only one of 20 crossings may nonetheless have decided during subjective questions that he or she would feel comfortable making the crossing in the future because there may have been no realization that that was a very high rate—an average likelihood of one risky crossing every 2 weeks if the individual commuted back and forth across the crossing daily. Research by Ayers et al. (1998) provides further insight into why confidence in crossing safety was much higher than warranted by the number of interventions. These researchers found that risk perception may not play as dominant a role in common behavioral choice as perception of whether an action can be completed successfully. Having completed a number of apparently successful crossings, participants may simply have ignored interventions or other indications of their risky decisions and based their ratings of crossing safety simply on the fact that they had made a number of safe crossings.

To understand the implications of the present research, in which most participants felt quite confident that they could safely cross at roundabouts and channelized turn lanes despite average performance data to the contrary, one must recognize that overestimation of safety is a common occurrence. Therefore the objective measure of safety—that is, interventions—is the most reliable (available) indication of crossing safety at roundabouts and channelized turn lanes. One should not be misled into thinking that crossings at these locations are safe because participants perceived them to be.

Viability of Interventions as a Measure of Risk

The accessibility framework applied in this research ultimately focuses on the concepts of pedestrian delay and risk. Pedestrian delay is reliably and objectively measured. The measurement of pedestrian risk is more challenging. The traditionally used objective measure of risk in the transportation field is the frequency and rate of collisions. Clearly, crash statistics are not applicable given the experimental design used, and consequently other surrogate safety measures need to be identified.

The selected safety measure of O&M interventions had been used in several prior studies involving crossings of blind pedestrians. The measure is related to the concept of traffic conflicts, which is an increasingly common safety performance measure. A traffic conflict is typically defined as an interaction between two vehicles (or a vehicle and a pedestrian) for which a collision is imminent pending an evasive action by any of the involved parties. The categorization for what constitutes a risky time-to-collision is typically defined by a 2-s threshold.

The approach of using O&M interventions as a surrogate safety measure uses a similar underlying principle. The O&M specialist intervenes when he or she feels that the crossing decision by the pedestrian would result in undue risk. For many of the interventions, it is likely that an actual collision could have been avoided if the driver had performed an emergency braking maneuver. However, this level of risk was deemed unacceptable to the pedestrian as well as to the approaching driver and any following vehicles.

Clearly, the intervention measure is subject to variability among different O&M specialists. It is human nature to have different perceptions of risk, and consequently it is expected that the threshold for an intervention may differ somewhat between two O&M experts. In this research, the team attempted to minimize this variability by having the same O&M specialist perform all the experimental trials.

The O&M intervention is further a coarse measure in that it stratifies pedestrian risk on a binary (yes/no) scale. In reality, the O&M interventions included a range of situations that represent varying degrees of risk that are difficult to define. For example, an intervention may include a multiple-threat situation at a two-lane approach where a pedestrian utilizes a near-lane yield by a heavy vehicle that masks visual and auditory information about a fast-moving vehicle in the far lane. On the other hand, an intervention may have occurred if the driver of a previously stopped vehicle accelerated at the same time that the pedestrian stepped out to utilize the yield. These events occurred in particular at the CTL, where traffic queues frequently spilled back across the crosswalk from the downstream merge point.

The intervention measure does not give a comprehensive safety assessment of the crossing attempts. Similar to collisions, interventions and conflicts are rare events that depend on a sufficiently large sample size. The fact that all of the sites exhibited some level of interventions (despite the relatively low sample size) speaks to their risk to the blind travelers. While no sighted pedestrians were involved in these experiments, it is hypothesized that a sighted participant would have been very unlikely to experience an O&M intervention rate at, for example, 16 crossing attempts at a single-lane roundabout, which is supported by research comparing blind and sighted pedestrians at roundabouts (NIH 2010).

The team attempted to develop a secondary measure of pedestrian safety by using expert ratings of video clips recorded during the trials. The approach aimed to extract potentially risky video clips that included, but were not limited to, all interventions recorded at a site. These short video clips were then shown in randomized order to a panel of expert reviewers, who rated pedestrian safety in the clip on a scale of 1 to 5. This approach was tested for the pretest condition at the CTL, but did not result in a reliable alternative to the intervention measure. The exercise did establish that there is agreement within most of the reviewers that events that resulted in O&M interventions were in fact risky. It further established that most of the control clips that were added to the sample to establish a baseline for safe behavior resulted in mostly low-risk ratings. However, the exercise proved inconclusive as far as any borderline risky events are concerned.

Overall, the activity gave the team confidence in the viability of the O&M intervention measure for pedestrian risk but did not result in any further information about safety performance. Due to project constraints, this approach was not applied to the remaining test sites. The team does believe, however, that there is merit in continuing research in this area. In particular, it would be beneficial to develop an objective performance of safety that is based on the field-measured time-to-collision based on vehicle trajectories (rather than on expert judgment). The results of the safety rating exercise are presented in Appendix H to be a resource for further research activities.

Driver Yielding and Enforcement

The treatments tested as part of NCHRP Project 3-78A all represented infrastructure-based treatments, which was a principal requirement of the project objectives and in keeping with Access Board guidelines. The analysis therefore did not include any treatments that would be carried by the pedestrian in the form of wayfinding or traffic detection technology. The scope further did not include any policy-based treatments such as increased law enforcement of yielding laws. Nonetheless, the results do seem to suggest that vehicle yields represent valid crossing opportunities that may be utilized by pedestrians who are blind, although at utilization rates less than 100%. Infrastructure treatments that resulted in increased yielding behavior and reduced vehicle speeds were shown to improve accessibility.

The motor vehicle codes in most U.S. states require drivers to yield to pedestrians *in* the crosswalk and in some cases even to pedestrians waiting *at* the crosswalk. However, field-observed yielding rates vary widely and are inconsistent across locations even with the same crossing treatment installed (Fitzpatrick et al. 2006). Most states offer additional protection to blind travelers to what is commonly referred to as "white cane laws." These are intended to promote driver awareness, courtesy, and yielding to pedestrians who identify themselves as having vision impairment, by either carrying a long white cane or by walking with a guide dog. The net benefit of increased driver yielding behavior is hypothesized to be greatest when traffic volumes are high since the occurrence of crossable gaps and all-quiet periods decreases. The fact that high yield compliance can result in low delays even under high volumes is made evident through the data from the PS-RAL single-lane roundabout, although it may also be associated with a safety trade-off. Despite a high AADT and heavy peak-hour flows, pedestrian delays were less than at the low-volume DAV-CLT roundabout. The difference is most likely attributable to a higher willingness of drivers to yield at the PS-RAL site. In this case, however, the PS-RAL site remained inaccessible to pedestrians due to a high rate of interventions.

In evaluating yielding behavior, two other considerations are important. First, the length of time a driver is willing to yield (i.e., driver patience) likely affects the ability of the pedestrian to utilize that yield. The detailed study results shown in Appendix A show that most participants required several seconds before crossing in front of a yielding vehicle, and some waited 10 s or more. Therefore, a yield that only lasts for a few seconds is unlikely to result in a utilized crossing opportunity for blind pedestrians. Second, the physical location of yields relative to the crosswalk is believed to affect the pedestrians' ability to detect these events. It is believed that the observed posttest increase in yield utilization at the two-lane roundabout for both treatments is at least partly attributed to the fact that drivers tended to yield closer to the crosswalk and therefore the rate of deceleration was more rapid. In other words, it seemed easier to detect a vehicle that quickly decelerated to a stop close to the crosswalk than one that slowly coasted to a stop farther from the crosswalk.

Interestingly, two data collection sites with different traffic conditions were located in Charlotte. At the tested single-lane roundabout, volumes were low and participants were delayed despite ample gap crossing opportunities as many waited for all-quiet periods. At the two CTL crossings, traffic volumes were much higher and the delay was exacerbated by a very high level of ambient noise from the main intersection. All three crossing locations were characterized by a low propensity of drivers to yield, which may be characteristic of the local driving culture or may be coincidence.

Implications for Facility Design

This section on implications for facility design is intended to advance the discussion in this area and to direct future research. The points below are based on field results from this and other studies as well as anecdotal evidence that evolved from observing many crossing attempts by blind travelers at different locations. Taken together, they comprise a toolbox for increasing the accessibility of crossings at CTLs, single-lane roundabouts, and two-lane roundabouts for pedestrians who are blind.

Channelized Turn Lanes

There is anecdotal evidence that a crosswalk located in the middle of the turn lane is preferable to a crosswalk at the upstream or downstream portion of the turn lane. The middle crosswalk establishes a short crossing path roughly perpendicular to the trajectory of turning vehicles (and therefore is useful for establishing alignment), and it physically separates the conflict of turning drivers and pedestrians with the downstream merge point. Based on turning radii and associated design speeds, this is also likely to be the location where speeds of right-turning vehicles are lowest. Since no alternate crosswalk locations were tested at the CTL (i.e., upstream or downstream), it is unclear from this research whether a different crosswalk location would have any (positive or negative) impact on the crossing ability of blind pedestrians.

Field tests suggested that high vehicle speeds contributed to the high incidence of unsafe crossings at the tested CTL; therefore, geometric designs and treatments intended to reduce vehicular speed, such as traffic-calming designs, raised crosswalks, pork-chop island design, narrow CTL width, small curve radii, and the absence of an acceleration lane may decrease the likelihood of unsafe crossing judgment by pedestrians who are blind. However, none of these treatments were tested in this research. Support for low turning-vehicle design speeds for CTLs is also given in the AASHTO *Guide for the Planning, Design, and Operation of Pedestrian Facilities* (2004). CTL designs with raised crosswalk have been observed in several cities across the United States.

No CTLs with acceleration lanes were studied in this research, but based on anecdotal evidence it is expected that they may further increase speeds and may result in low compliance with crosswalk laws and installed treatments.

Dual-lane CTLs are included in the draft PROWAG as facilities where a pedestrian-actuated and APS-equipped signal meets the accessibility requirements. While no dual-lane CTLs were part of this research, the crossing challenges observed at the tested single-lane CTL suggest that dual-lane CTLs may in fact be very challenging places to cross for a pedestrian who is blind. With two lanes, the expected challenges are related to higher volumes, higher speeds, and a risk of multiple-threat situations, compared to single-lane CTLs.

Detectable warnings complying with the draft PROWAG are required at both curb and island ends of crosswalks to warn pedestrians who are blind that they are leaving the pedestrian way and entering the vehicular way.

A potential treatment that facilitates the auditory discrimination of right-turning (conflicting) and through traffic should be considered and studied further. The sound strips tested in this research generally served their intended purpose; however, the selected type of material evaluated proved to be too quiet given the high ambient noise at the test site. The biggest problems with the treatment arose when vehicles were traveling very slowly and the audible cues from the sound strips were not noticeable.

The use of a pedestrian signal at the CTL is a possible treatment that can be tied in with the existing signal control at the main intersection. There are some challenges to tying the CTL signal into the existing controller, especially when an intersection has multiple CTLs that are to be signalized. But an existing signal phasing strategy is to use vehicle overlap phasing with a pedestrian signal across the crosswalk. If adding the CTL signal to an intersection with a long cycle, the expected pedestrian delay may be high and needs to be assessed in the context of the total pedestrian crossing. At a busy intersection such as the test site, a diagonal pedestrian crossing (e.g., from the southeast to northwest corner) would entail the use of four signalized crossings (CTL, main road, side road, CTL). Signalized CTLs have been observed in several cities across the United States and are rather common in other countries.

In addition to a standard pedestrian-actuated signal, a PHB may be another alternative for CTLs. The advantages of the allowable vehicle movements during the "Flashing Red" phase are reduced with shorter crossings and associated shorter "Flashing Don't Walk" phases. However, some vehicle delay savings are expected to remain. The allowable provision in the MUTCD to let the pedestrian display at the PHB rest in a dark mode may be considered for CTLs since many (sighted) pedestrians may not require the added assistance provided by the signal.

Single-Lane Roundabouts

The design of single-lane roundabouts should encourage low vehicle speeds in the vicinity of the crosswalk. Low speeds are shown to correlate with increased yielding behavior and reduced injury in case of a collision. There is some concern that lower speeds (and associated lower vehicle noise) may reduce the ability of a blind pedestrian to detect crossing opportunities (yields), which is a question that deserves the attention of researchers.

The design of a single-lane roundabout should encourage narrow (or standard) lane widths in the vicinity of the crosswalk. Lanes that flare out too early unnecessarily increase the crossing distance for pedestrians and further may allow vehicle passing in the vicinity of the crosswalk, thereby creating a potential multiple-threat situation. This was observed at one of the three tested single-lane roundabouts and resulted in some near-interventions.

Detectable warnings complying with the draft PROWAG are required at both curb and island ends of crosswalks to warn pedestrians who are blind that they are leaving the pedestrian way and entering the vehicular way. Also, planting strips along the sidewalk serve as a barrier that discourages pedestrian access to the roadway at places other than the crosswalk and make it less likely that a blind pedestrian will inadvertently step from the paved walkway into the paved roadway at any point other than the crosswalk or begin crossing from the wrong point without realizing the intersection is a roundabout. They also provide a trailing surface that long cane users can use to locate the crosswalk.

The splitter island should be wide enough for pedestrian refuge and to enable a two-stage crossing. Note that splitter islands that are not raised islands but are simply painted on the pavement are not detectable to blind pedestrians.

Several blind pedestrians commented that landscaping and trees on the splitter island (at the two-lane roundabout) blocked some of the sound from the lane behind them when they were crossing from the island to the curb. This helped with sound separation and discrimination of the traffic coming toward them from the traffic going away from them, and may therefore be beneficial for single-lane roundabouts as well. Landscaping on the splitter islands should not block the view of the crosswalk for drivers.

Two-Lane Roundabouts

The two-lane roundabout design should promote low speeds at the crosswalk through geometric design, where possible, or through supplemental traffic-calming treatments (bulb-outs or raised crosswalks). The raised crosswalk design showed potential at the tested location and resulted in significantly reduced pedestrian delay and interventions; however, there is concern related to observed multiple threat conflicts, and more research is need to clarify risk. The impact on traffic operations is believed to be directly related to the design of the raised crosswalk (vertical elevation and transition slope). In the tested installations, vehicle impacts were reasonable. More testing is necessary to ensure that this treatment has broader application to other geometries and traffic patterns.

The use of a PHB showed promise at the tested location in terms of reducing pedestrian delay and interventions, but was associated with some misunderstanding and/or noncompliance on the side of drivers and blind study participants. A simulation-based sensitivity analysis showed that the use of the PHB phasing, a two-stage crossing, and an offset exit portion of the crosswalk all result in improvements to vehicular operation compared to a standard one-stage pedestrian-actuated signal. If signalization is considered at a two-lane roundabout, these alternate signalization strategies should be considered.

Detectable warnings complying with the draft PROWAG are required at both curb and island ends of crosswalks to warn pedestrians who are blind that they are leaving the pedestrian way and entering the vehicular way. Also, planting strips along the sidewalk serve as a barrier that discourages pedestrian access to the roadway at places other than the crosswalk and make it less likely that a blind pedestrian will inadvertently step from the paved walkway into the paved roadway at any point other than the crosswalk or begin crossing from the wrong point without realizing the intersection is a roundabout. They also provide a trailing surface that long cane users can use to locate the crosswalk.

The splitter island should be wide enough for pedestrian refuge and to enable a true two-stage crossing. Several blind pedestrians commented that the landscaping and trees on the splitter island blocked some of the sound from the lane behind them when they were crossing from the island to the curb. This helped with sound separation and discrimination of the traffic coming toward them from the traffic going away from them. Landscaping on the splitter islands should not block the view of the crosswalk for drivers.

Additional physical separation of the crosswalk from the circulating lane may be considered in the design of the two-lane roundabout to separate driver decision points and to provide added queue storage at the exit leg for yielding drivers. However, a crosswalk too far from the circle may lose the roundabout's traffic-calming effect, which reduces speeds and encourages yielding. Low design speeds and traffic-calming treatments may mitigate that tradeoff.

Wayfinding and Alignment Treatments

This research was primarily focused on the aspect of accessibility that is related to the actual decision of when to initialize a crossing. As discussed earlier in this report, the full accessibility of a crossing involves three other critical tasks: (1) locating the crosswalk, (2) aligning to cross, and (3) maintaining alignment during crossing. Several treatments are available that can assist in these important accessibility tasks. Ongoing research for the NIH (2010) is currently comparing the effectiveness of various wayfinding and alignment treatments. However, even today anecdotal evidence suggests that certain facility design elements and supplementary treatments can be valuable assets to blind travelers.

The task of locating crosswalks at roundabouts and CTLs is challenging because crosswalks in these situations are not located at corners. Unless pedestrians who are blind are aware that they are approaching a roundabout or CTL crossing, it is common for them to continue around the bend without realizing for some time, if at all, that they have gone past the crosswalk. This is true both for those who travel using a long cane and those who use guide dogs. Design elements that help pedestrians locate the crosswalk are landscaping along the curb except at the crosswalk, and the presence of a curb ramp at the crosswalk. This landscaping also may provide a clue to blind pedestrians that the intersection is a roundabout. When the sidewalk is paved to the curb, blind pedestrians may assume they are at a rounded corner and cross at the point where they detect a curb roughly in front of them, which would result in them crossing the circulatory roadway. However, many pedestrians who are blind prefer to travel near the edge of a sidewalk that is furthest from the street. In this case, unless they are specifically looking for a non-corner crossing, they may not be aware of either a break in a landscaping strip or a curb ramp. For those who travel using guide dogs, detecting the break in a landscaping strip or a curb ramp requires the use of special strategies.

Two treatments are currently suggested for providing effective cues to the location of crosswalks that are not where they are expected. At a crossing with an accessible pedestrian signal, placement of the pushbutton with its pushbutton locator tone immediately beside the curb ramp leading to the crosswalk provides an audible cue to the presence and location of a crosswalk. This feature was noted by pedestrians during the Golden two-lane roundabout posttest with the PHB. A 24-in.-wide strip of a linear texture, sometimes referred to as a "bar tile," running perpendicular to the sidewalk and across the entire width of the sloped ramp, provides a tactile cue that can be detected underfoot and by use of the long cane. Use of linear textures is uncommon in the United States at present but has been required or is commonly used to guide pedestrians who are blind to crosswalks in other countries (Bentzen, Barlow, and Franck 2000).

The task of properly aligning to cross can be assisted by a "square" geometry. At a conventional four-legged intersection, blind pedestrians can often align using the cues of adjacent and perpendicular traffic. Since traffic patterns at roundabouts and channelized turn lanes are on curved trajectories, additional alignment cues may be needed. Directional tactile surface lines that are accessed by foot and installed concurrent with detectable warnings have some potential, as do returned curb installations that provide a hard edge on each side of the crosswalk ramp that is in line with the direction of travel on the crosswalk. Another potentially effective treatment option involves presenting an auditory signal from the far side of the crosswalk (for example, through an audible device). A far-side audible signal could also be expected to assist with the task of maintaining alignment during crossing. Other alignment treatments are *raised markings* that delineate the crosswalk or *guidance strips* that can be raised parallel to the crosswalk.

The Access Board draft PROWAG and other U.S. Access Board resources provide additional detail on these and other wayfinding and alignment treatments. The reader is encouraged to refer to these references for further information.

Future Research Needs

This research provided a proposed framework for pedestrian accessibility and presented field study results and other material to inform the ongoing nationwide discussion of the accessibility of roundabouts and CTLs. Clearly there are limitations to this research, which are most notably tied to the number of sites that could be captured in the field studies.

The number of roundabouts in the United States has grown over the course of this project. When the project team was looking for sites, we had difficulty finding roundabouts with appropriate features, in areas where there were adequate numbers of blind pedestrians, and in municipalities that were interested in testing various treatments. Now there are examples of roundabouts in various locations with some features that may address accessibility for pedestrians who are blind, for example, yellow pedestrian-actuated beacons installed at the Bird Rock corridor roundabouts in the San Diego area, and other municipalities that are considering the installation of PHBs and raised crosswalks. An ADA-complaint/legal action in Oakland County, Michigan, resulted in court-ordered testing of treatments at two three-lane roundabouts. This study and other activities will provide additional information, which in combination with results of NCHRP Project 3-78A, can give more guidance and comparisons for evaluation of treatments in other locales. But there is much more that needs to be explored in developing crossing solutions for pedestrians with vision disabilities at roundabouts and channelized turn lanes.

This research showed serious accessibility problems at the selected CTL site and that the low-cost/low-impact treatments were not sufficient to establish accessibility at that site. Since the number of CTLs currently far outnumbers roundabouts, additional research is needed that field tests treatments at CTLs and further investigates issues at different CTL designs. Specifically, two additional CTL studies are proposed: (1) testing of a traffic calming treatment such as the raised crosswalk or a pedestrian hybrid beacon at high-volume and high-speed locations, and (2) testing of low-cost treatments (sound strips and flashing beacons) at low-volume and low-speed locations. This additional research would greatly aid the understanding of crossing challenges at CTLs and would lead to the development of a more extensive treatment catalogue for these locations.

As discussed earlier in this chapter, little is known about the impact of education and training on the behavior of blind pedestrians, and little is known about how different movements or crossing strategies of pedestrians who are blind might affect driver behavior. Both could be fruitful areas for more exploration and research. First, the team observed a number of different techniques used by blind pedestrians in crossing, getting the attention of drivers, and detecting yields, but at this point it is unknown what strategies and techniques work best. Second, there is a need for training programs for pedestrians who are blind, although there is currently no consensus on the form and extent of this training. Consequently, there is a need for determining effective strategies and techniques for determining that an intersection is a roundabout, locating the crosswalks, aligning to cross, determining a safe time to cross, and maintaining alignment while crossing. Developing a training program that could be used by O&M specialists and supported by state DOTs may be a direction to explore further.

Future research should perform field testing of additional two-lane roundabout treatments. In particular, more testing is needed to determine under what conditions (geometry, traffic) a particular treatment is most appropriate. This research identified two treatments (raised crosswalk and pedestrian hybrid beacon) that showed good potential at the tested two-lane roundabout. These findings should be validated with additional testing, including some at higher-volume roundabouts. Since the potential signalization of two-lane roundabouts is a politically sensitive topic, additional research would give engineers, policy makers, and the U.S. Access Board a more complete understanding of the crossing challenges. In particular, research may get closer to developing actual requirements and thresholds for the installation of pedestrian signals at two-lane roundabouts with the objective of enhancing the accessibility and usability to pedestrians who are blind. In addition, more research should be done to test low-impact treatments at low-volume two-lane roundabouts. Future studies should evaluate the use of, for example, rectangular rapid-flashing beacons (RRFBs) and other flashing beacons, as well as traffic-calming treatments that are more suitable for cold climates or other regions where raised crosswalks may not be allowed in public rights of way.

While some of the tested single-lane roundabout crossings may be deemed accessible under prevailing traffic conditions, the analysis did point to some areas of concern, including unexpectedly high delays at one low-volume site (DAV-CLT) and high interventions at a high-volume location (PS-RAL). The team believes that low-cost treatments could enhance blind pedestrian access at these locations. Future tests should explore the impacts of traffic-calming treatments (e.g., raised crosswalks) and auditory treatments such as sound strips. Flashing beacons may further improve driver awareness of pedestrians and promote yielding in the right environments, and more research could clarify where treatments are most useful.

In addition, there is a need for new and improved field-based risk performance measures to provide a more objective and consistent assessment of risk and safety. The NCHRP Project 3-78A analysis was limited to the use of O&M interventions as a measure of pedestrian risk, which from an analysis perspective has the drawback of being a relatively rare event. The availability of a more readily observed and continuous measure of risk could facilitate the development of safety prediction models (similar to the mixed-priority delay models) and could further guide the process of surrogate safety assessment in simulation. Potential new risk measures include the time-to-collision measured at the time a pedestrian steps into the crosswalk or the necessary deceleration rate of vehicles to come to a stop prior to the crosswalk. Chapter 6 discussed some initial efforts and demonstrations showing that it is feasible to obtain these data from field and/or video-based measures (Schroeder 2008), and work is currently underway in applying these concepts to multi-lane roundabouts (NIH 2010).

A field-based validation of the mixed-priority delay models and work toward extending these models to data from additional sites would provide greater confidence in the modeling. Due to the limited data available in this research, all observations were used for model development. If the models were validated against other sites, analysts would likely have much increased confidence in their viability.

Finally, future research should include an increased focus on the auditory environment in the vicinity of the crosswalk to gain a better understanding of the relationship of traffic volumes, associated noise patterns, and ultimately the challenges to blind travelers to identify crossing opportunities based on auditory cues. Anecdotal evidence from this research suggests that pedestrians are able to readily cross during all-quiet periods while hesitating or waiting during times of high ambient noise, although this strategy raises concerns in light of more frequent occurrence of quiet (hybrid) vehicles (Wall Emerson and Sauerburger 2008). However, most crossing situations occur somewhere on the continuum between these very quiet and very loud conditions, and it is unclear what types of sound environments and cues are most difficult or most helpful to the blind pedestrian.

In closing, significant work remains to be done in this area that focuses on additional treatments, and most importantly, on extending these findings to more locations that are different geometrically and/or from a traffic operational perspective. This report has established a framework and analysis methodology that is readily extended and applied to other sites and that will allow future research efforts to be tied directly to findings from this report. The ongoing national debate on the accessibility of modern roundabouts and CTLs has spurred municipalities to take the initiative and tackle some of these accessibility issues prior to the completion of this report and prior to the final adoption of PROWAG. Additional research should take advantage of this momentum and perform controlled pretest–posttest evaluations at these locations as treatments are being installed. A significant amount of time in this project was devoted to selecting treatments and identifying municipalities willing to install them for study. With already-planned installations, additional research can make very efficient use of project resources by focusing on the field studies and data analysis of these locations.

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APPENDIX A

Detailed Results

This appendix contains five parts detailing analysis results for the different studies performed under NCHRP Project 3-78A:

Part 1: Detailed Channelized Turn Lane Results
Part 2: Detailed Single-Lane Roundabout: Golden, CO
Part 3: Detailed Single-Lane Roundabout: North Carolina
Part 4: Detailed Two-Lane Roundabout: Golden, CO – RCW
Part 5: Detailed Two-Lane Roundabout: Golden, CO – PHB

CONTENTS

PART 1

Detailed Channelized Turn Lane Results

Introduction

This section describes detailed analysis results of data collected at the channelized right turn lane in Charlotte, NC, at the intersection of Providence Road and Pineville-Matthews Road (Exhibit 1). The focus is on pedestrian-related measures, including the availability and utilization of yield and gaps, as well as pedestrian delay and O&M interventions.

Two turn lane crosswalks at the CTL sites were studied in this project: the crosswalks in the southeast (SE) and northwest (NW) corner. Both turn lanes served the right-turn movements from Providence Road onto Pineville-Matthews Road. Similar to other data collection sites, the CTL was studied in a pre and post study design with treatment installation. The treatments were (1) sound strips that were intended to increase the awareness of pedestrians of approaching vehicles at the NW corner and (2) sound strips in combination with a pedestrian-actuated flashing beacon that was intended to increase driver yielding behavior at the SE corner. In the following discussion, the crosswalks will be identified by treatments installed as SS-ONLY and SS+FB, respectively. Both turn lanes were further supplemented with lane delineators that were intended to prevent late merges into the turn lane. All treatments, including the lane delineators, were installed between pre and post studies.

The pre study was completed in May 2008; a total of 16 blind travelers participated. Fourteen of the original 16 participants returned for the post experiment in November 2008. The treatments were installed in early October 2008, allowing six weeks for driver adaptation.

CTL Analysis Results

Site Description

The CTL site is located at the intersection of two major arterial streets in southeast Charlotte. Providence Road has a four-lane cross-section, and Pineville-Matthews Road has a six-lane cross-section in the vicinity of the intersection. All four left-turn movements have dual left-turn lanes and are thus controlled by protected signal phases. In the PRE condition, all right-turn lanes were free flowing (no signal) and were controlled only by a downstream yield sign. As a result, vehicle speeds through the turn lane were relatively fast. Vehicle movements were entirely uninhibited and free flowing during signal phases where the downstream lanes were clear, which were the signal phases serving the adjacent through movements on Providence Road and the opposing left turns on Pineville-Matthews Road.

The treatments tested at the CTL site were intended to provide a relatively low-cost solution to make the site accessible to and usable by pedestrians who are blind. The high-end treatment would have been a pedestrian signal, which was not tested because its effects on crossing performance are predictable. The treatment tested was sound strips that enhance the auditory sound patterns of approaching vehicles. The hypothesis was that sound strips enhance the rate of opportunity utilization of pedestrians and therefore reduce delay. Presumably, sound strips would also help reduce the rate of O&M interventions if the subjects have increased awareness of the presence of a vehicle in the turn lane. The sound strips were tested in isolation at the SS-ONLY corner; Exhibit 2 shows a photo of the installation along with the mentioned lane delineators.

At the SS+FB corner, the sound strip and lane delineator treatment was supplemented with a pedestrian-actuated flashing beacon (Exhibit 3). The FB was intended to increase driver awareness of the pedestrian's intent to cross and thus increase the rate of yielding. When activated, the FB would transmit an audible speech message saying "Flashing Beacon Is On" for the duration of the flashing mode. The flashing mode would terminate after 20 s.

Crossing Statistics for CTL Site and Treatments

The analysis of crossing performance focuses on aspects of pedestrian–vehicle interaction following the NCHRP Project 3-78A analysis framework. The first analysis component describes the availability and utilization of yields in both the

Exhibit 1. Aerial view of CTL site.

Photo by Google

pre and post treatment conditions. Two yield measures were used in the analysis:

- **P(Y_ENC):** The probability of encountering a yield event, defined as the number of yields divided by the total of all events encountered by the pedestrian until he/she completes the crossing.
- **P(GO|Y):** The probability of yield utilization, defined by the number of crossings in a yield divided by total number of yields encountered by the pedestrian.

The P(Y_ENC) measure is somewhat different from the traditionally used probability of yielding since it is calculated on the basis of all pedestrian–vehicle events and not just potential yielders. Chapter 3 provides additional discussion on these and other performance measures, including examples on the difference between the yielding measures.

Exhibit 2. Sound strip installation at CTL.

Photo by Bastian Schroeder

Exhibit 3. FB installation at CTL.

Photo by Bastian Schroeder

Treatments at the SS-ONLY crosswalks were sound strips and lane delineators only; the SS+FB corner was further supplemented with a pedestrian-actuated flashing beacon. The figures shown represent the mean results considering all subjects. Each subject completed ten crossing *trials* at the roundabout, with each trial consisting of two *lane* crossings (e.g., curb to splitter island and island to curb). For example, a subject in the pre condition would have crossed each crosswalk 20 times (twice in each of 10 trials) and would have performed a total of 40 crossings at the site. The average performance for each crosswalk in the pre condition was then calculated from the mean of these 20 crossing for all 16 subjects. In the post conditions, 14 subjects participated in the experiment. In total, 30 subjects were included in the study (16 pre, 14 post) and each performed 40 lane crossings, resulting in a theoretical total of 1,200 crossing attempts at this site. However, several subjects appeared to struggle with too many crossing attempts, and the number of trials per crosswalk was therefore capped at six for some participants. Overall, 993 crossings were completed by the participants. Exhibit 4 shows the statistics for the studied crosswalks pre and post treatment installation.

Exhibit 4 shows that the probability of encountering a yield, P(Y_ENC), was not significantly different at the two studied crosswalks in the pre condition ($p = 0.2728$).The installation of the sound strips and lane delineators at the SS-ONLY corner did not result in a notable change in yield encounters. The added installation of the flashing beacon increased the likelihood of encountering a yield from 15.2% to 22.0%, which is small but significant at $p = 0.0363$. From a driver perspective

Exhibit 4. Yield availability and utilization statistics for CTL crosswalks.

a) P(Y_ENC)

Pre	Avg.	Min.	Max.	Std. Dev.
SS-ONLY (n = 16)	18.4%	4.2%	37.5%	8.3%
SS+FB (n = 16)	15.2%	6.0%	36.4%	7.9%
Post				
SS-ONLY (n = 14)	18.6%	10.0%	75.0%	20.6%
SS+FB (n = 14)	22.0%	0.0%	35.7%	8.9%

b) P(GO|Y)

Pre	Avg.	Min.	Max.	Std. Dev.
SS-ONLY (n = 16)	50.8%	0.0%	100.0%	31.0%
SS+FB (n = 16)	53.1%	8.0%	100.0%	28.5%
Post				
SS-ONLY (n = 14)	40.5%	10.0%	75.0%	20.6%
SS+FB (n = 14)	64.6%	20.0%	100.0%	28.2%

[P(Yield), which is not shown in Exhibit 4], the rate of yielding increased from 24.1% to 43.1% (p = 0.0123). This means that with the installation of the FB, 43% of drivers stopped at the beacon, but these events still only represented 22.0% of the encountered vehicle events. The remaining events are in the form of gaps.

The exhibit further shows the rates of yield utilization, P(GO|Y), defined as the rate of yields that resulted in a pedestrian crossing the roadway. The yield utilization rates at the SS-ONLY corner actually appeared to decrease from 50.8% to 40.5%, although that change is not statistically significant (p = 0.2878) due to a high standard deviation. Similarly, the apparent increase in P(GO|Y) at the SS+FB corner from 53.1% to 64.4% is not significant at the given sample size (p = 0.2769). The high standard deviations in the yield utilization measure suggest great inter-subject variability. In the range of P(GO|Y), it is evident that some pedestrians had perfect yield utilization, while others utilized only 8% to 10% of yield opportunities.

A fraction of yields further fell into the "forced yield" category, which is defined as the pedestrian stepping out into the roadway before the vehicle initiated the yielding process. The degree of risk associated with these events depends on the relative position and speed of the vehicle at the time of crossing initiation. Forced yield events should therefore not necessarily be interpreted as poor or risky decisions. In the pre condition, 11.3% and 11.5% of yields were forced at the SS-ONLY and SS+FB crossings, respectively. In the post condition, the corresponding forced yield percentages were reduced to 6.3% and 5.9%. This reduction in the percentage of forced yields was not statistically significant due to high standard deviations (p = 0.3520 and p = 0.1902 for SS-ONLY and SS+FB, respectively).

The analysis next considered the availability and utilization of crossable gaps. For the purpose of this analysis, a crossable gap was defined as a gap greater than 6.5 s, which was sufficient to cross the 16-ft crosswalk at a walking speed of 3.5 ft/s while allowing for a 2-s buffer. These 2 seconds allowed for some pedestrian reaction time before initiating the crossing, as well as a safety buffer between a completed crossing and the next vehicle arrival. Similar to the yield statistics, two gap-related parameters are defined:

- **P(CG_ENC):** The probability of encountering a CG event (gap greater than 6.5 s), defined as the number of crossable gaps divided by the total of all events encountered by the pedestrian.
- **P(GO|CG):** The probability of crossable gap utilization, defined by the number of crossings in a CG divided by total number of CGs encountered by the pedestrian.

Exhibit 5 shows the statistics for the studied crosswalk.

The results in Exhibit 5 show a slightly higher P(CG_ENC) at the SS+FB crosswalk, which is significant at p = 0.0554. With the installation of the treatments, the rate of crossable gap encounter increases for both the SS-ONLY and SS+FB crosswalks, but neither increase is significant given the high standard deviations across subjects (p = 0.1666 and 0.4440, respectively).

The rates of gap utilization are again comparable between SS+FB and SS-ONLY crosswalks in the pre condition. While the SS-ONLY treatments did not significantly affect gap utilization (p = 0.4238), the added installation of the flashing beacon increased P(GO|CG) from 63.2% to 89.3% at the SS+FB crosswalk (p = 0.0011). The effect may be attributable to an increased level of confidence resulting from the speech message emitted from the beacon.

Exhibit 5. Crossable gap availability and utilization statistics for CTL crosswalks.

a) P(CG_ENC)

Pre		Avg.	Min.	Max.	Std. Dev.
	SS-ONLY (n = 16)	34.9%	16.9%	64.7%	11.3%
	SS+FB (n = 16)	44.7%	27.9%	84.6%	16.1%
Post					
	SS-ONLY (n = 14)	41.2%	24.7%	62.1%	12.8%
	SS+FB (n = 14)	49.2%	29.1%	75.0%	15.6%

b) P(GO|Gap>Min)

Pre		Avg.	Min.	Max.	Std. Dev.
	SS-ONLY (n = 16)	60.3%	4.0%	100.0%	28.9%
	SS+FB (n = 16)	63.2%	10.0%	100.0%	24.9%
Post					
	SS-ONLY (n = 14)	68.2%	5.8%	100.0%	24.4%
	SS+FB (n = 14)	89.3%	58.3%	100.0%	13.4%

The combined effect of gap and yield availability and utilization is reflected in the delay experienced by pedestrians. Delay statistics in Exhibit 6 are provided for two delay measures:

- **Observed Delay per Leg (s):** The average pedestrian delay in seconds, defined as the time difference between when the trial started and when the pedestrian initiated the crossing.
- **Delay>Min (s):** The delay beyond the first opportunity (Delay>Min), defined as the time difference between first yield or crossable gap encountered by the pedestrian and the actual crossing initiation.

Statistics for all measures are for crossing one lane of channelized turn lane.

Exhibit 6 shows similar delays and Delay>Min at both turn lanes in the pre condition ($p = 0.6972$). As was the case for the roundabout sites, the observed ranges and standard deviations of the delay estimates are large, suggesting great variability across subjects. The highest average delay in the pre study was 80.6 s for one subject, while another one had an average delay of only 3.7 s across all trials.

Exhibit 6. Average pedestrian delay statistics for studied crosswalk.

a) Observed Delay per Leg (s)

Pre		Avg.	Min.	Max.	Std. Dev.
	SS-ONLY (n = 16)	26.2	3.7	80.6	20.7
	SS+FB (n = 16)	23.4	4.1	75.7	19.6
Post					
	SS-ONLY (n = 14)	18.5	5.3	34.5	9.2
	SS+FB (n = 14)	12.2	3.2	36.0	8.0

b) Delay>Min (s)

Pre		Avg.	Min.	Max.	Std. Dev.
	SS-ONLY (n = 16)	15.6	0.3	65.4	17.4
	SS+FB (n = 16)	14.9	0.6	63.4	16.9
Post					
	SS-ONLY (n = 14)	11.7	2.1	27.9	7.5
	SS+FB (n = 14)	4.9	0.0	20.4	5.7

With installation of the treatments, the SS-ONLY delay dropped from 26.2 s to 18.5 s, which is not statistically significant at $p = 0.1898$. However, it is evident that both the range of observed delays and the standard deviation of the estimate showed corresponding reductions, suggesting at least some impact from the sound strip installation. The SS+FB corner saw a higher delay reduction, from 23.4 s to 12.2 s, which is significant at $p = 0.0453$. Again, both the range and standard deviation of the delay estimate show a reduction, suggesting more consistent behavior across subjects after treatment installation.

The single highest delays for any subject in a trial were 119.0 and 113.1 s in the pre and post conditions, respectively, excluding events that were capped at the 2-min time-out limit. Overall, at the SS-ONLY crosswalk the 2-min limit was reached 19 times in the pre and 16 times in the post study (with two fewer subjects participating). At the SS+FB crosswalk the time-out was reached 10 and 2 times in the pre and post, respectively. So despite average delay improvements, isolated trials still performed very poorly after treatment installation.

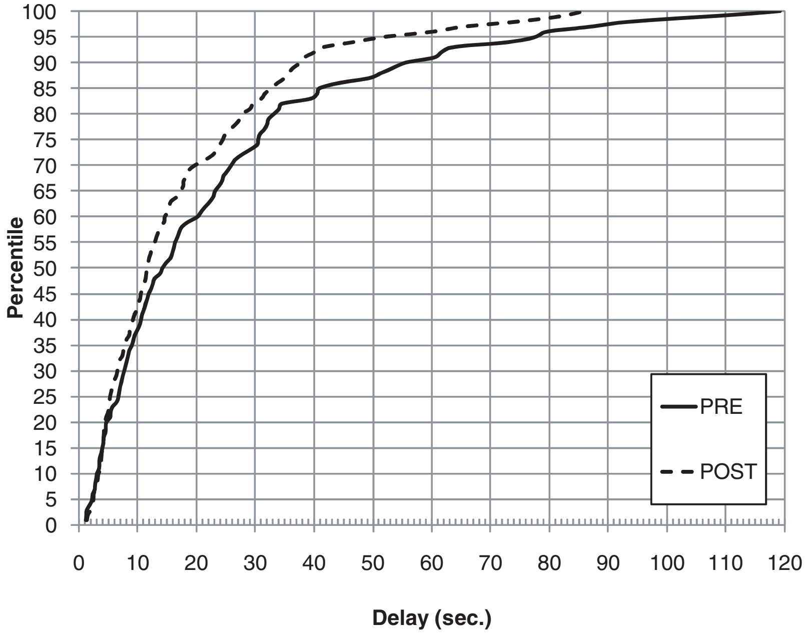
The results for Delay>Min also show corresponding trends. There was no significant difference between SS+FB and SS-ONLY in the pre condition ($p = 0.9089$). A small but statistically insignificant drop was evident for the SS-ONLY corner (15.6 to 11.7 s, $p = 0.4224$), while the SS+FB corner saw a significant reduction from 14.9 to 4.9 s ($p = 0.0342$). The difference between delay and Delay>Min suggests that quite a few participants missed crossing opportunities, especially when considering the range and standard deviation of the estimates. Similar to delay, the Delay>Min parameter saw some tightening in these variability measures after treatment installation.

Exhibit 7 shows the cumulative distribution of delay for all subjects in the pre and post conditions for both SS-ONLY (a) and SS+FB (b) crosswalks. The figures show a relative shift of the pre and post curves for both crosswalks, with a bigger effect expectedly at the SS+FB corner. The 85th percentile overall delay was reduced from 40.9 to 32.7 s at the SS-ONLY corner, and from 38.6 s to 17.9 s at the SS+FB crosswalk.

Exhibit 8 shows the 85th percentile delay estimate by subject for SS-ONLY (a) and SS+FB (b) crosswalks. The exhibit makes evident that there is a lot of inter-subject variability.

Exhibit 7. Cumulative delay distribution all subjects – channelized turn lane.

a) SS-ONLY



b) SS+FB

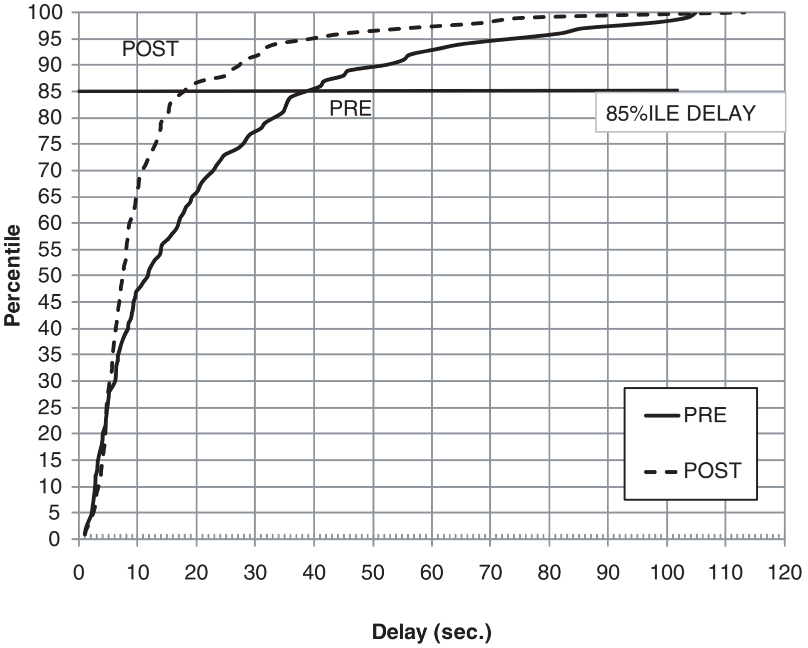
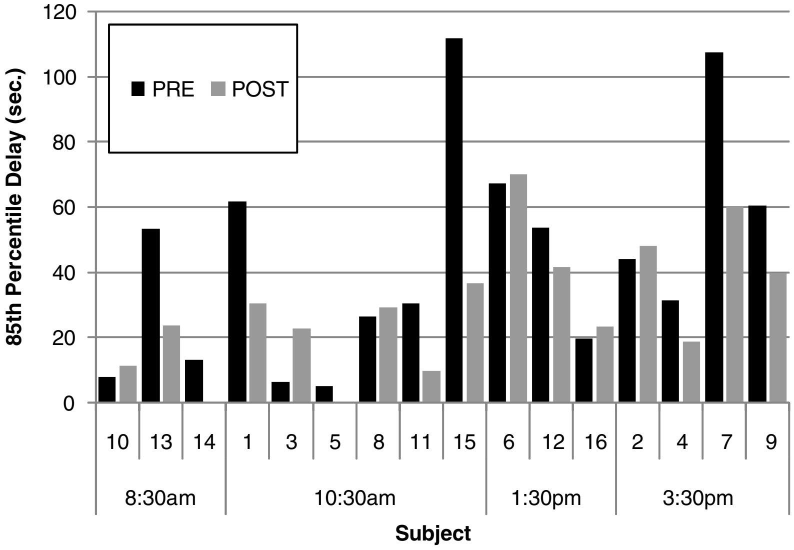
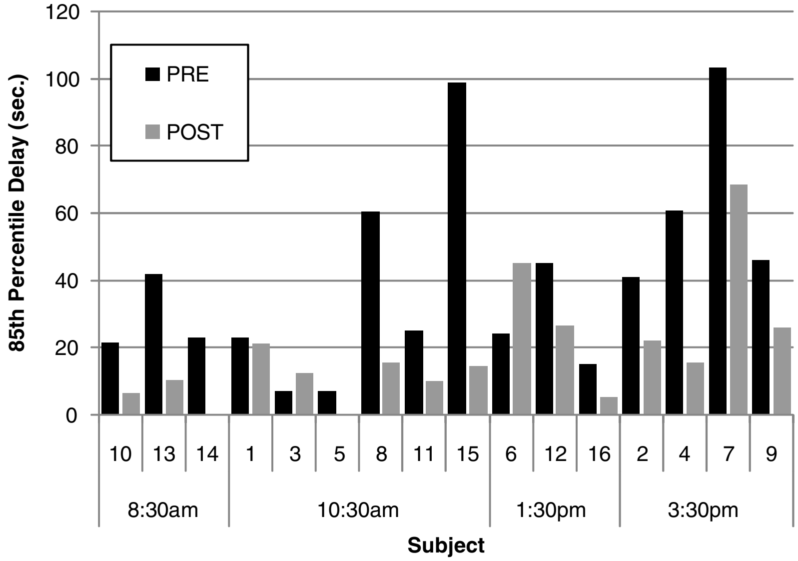


Exhibit 8. 85th percentile delay by subject – channelized turn lane.

a) SS-ONLY



b) SS+FB



The results of the SS-ONLY crosswalk show that some participants seemed to benefit from the sound strips (subjects 1, 4, 7, 9, 11, 12, 13, and 15), while others experienced no difference (subjects 2, 6, 8, 10, and 16). One subject experienced greater delay after treatment installation (subject 3). Note that subjects 5 and 14 did not participate in the post study.

For the SS+FB crosswalk, Exhibit 8 shows that several participants experienced reductions in 85th percentile delay after installation of the treatments (subjects 2, 4, 7, 8, 9, 10, 11, 12, 13, 15, and 16), while others stayed approximately constant (subjects 1 and 3) and one actually experienced slightly higher delay after the treatment was installed (subject 6). Subjects 5 and 14 did not participate in the post study.

The results are further arranged by time of day. It appears that participants in the 8:30 a.m. time slot experienced lower delay than those participating later in the day, when traffic volumes were higher. However, given the low sample of observations in each category, no effect can be isolated. Most participants were in the 10:30 a.m. time slot, during which a range of delay times was observed.

The analysis further investigated two parameters that were intended to describe the efficiency with which crossing opportunities were utilized:

- **Latency (s):** Latency is defined as the time between when the previous vehicle went through the crosswalk and the time the pedestrian initiated the crossing.
- **Yield Lost Time (s):** The YLT is defined as the time between when a driver first yields and the time the crossing is initiated. Note that in some cases, pedestrians may prefer to cross only after a car has come to a full stop (stopped yield), and so some inherent yield utilization time is expected.

Exhibit 9 shows statistics for both measures.

The latency results in Exhibit 9 suggest that on average pedestrians waited 8 to 10 s into a crossable gap before initiating the crossing in the pre study. This suggests a lot of inefficiency in decision-making and likely contributes to the low overall rate of gap utilization at the site. Individual subjects even experienced average latency times up to 32 s. With installation of the treatments, the average latency dropped at the SS+FB crosswalk from 10.0 to 6.8 s ($p = 0.0986$). It appears that the combination of sound strips and flashing beacon either gave pedestrians more confidence in their actions or that the sound strips helped with identifying gap crossing opportunities (in this case through the absence of sound).

For the yield lost time measure, there was no measurable difference between SS-ONLY and SS+FB corners and no detectable impact with treatment installation. The average YLT was in the range of 3 to 4 s, which again points to inefficiencies in the utilization of yields. Similar to observations at roundabouts, isolated YLTs reached a maximum average of 18.3 s. It is expected that few drivers are willing to wait that long to let a pedestrian cross, unless they experience a downstream conflict and therefore do not incur any additional delay. At the CTL, there may be a downstream queue resulting from vehicles yielding to cross-street traffic. At the same time, these high YLTs prove that there are some determined yielders that disrupt traffic operations similar to the way a signalized crossing would, or even more so. For the 16-ft crossing, a pedestrian signal would likely be timed as 4 s of "Walk" followed by 5 s of "Flashing Don't Walk" (16 ft/3.5 fps = 4.6 s), which is significantly less than the time some drivers yielded. Presumably, a PHB or HAWK phasing scheme would further reduce the signal impact.

Finally, the analysis evaluates the rate of O&M interventions, a measure of pedestrian risk during the crossings. The study participants were at all times accompanied by a certified O&M specialist, who was directed to stop the participants if the crossing decision would have resulted in undue risk to pedestrian and/or driver. The resulting rate of O&M intervention is defined as follows:

- **Intervention Rate (%):** The intervention rate is defined by the number of times the O&M specialist intervened for a particular subject divided by the total number of lanes crossed for a particular condition. For example, one intervention over a set of 20 lane crossings at one turn lane corresponds to an intervention rate of 5%.

The summary statistics for O&M interventions are given in Exhibit 10.

The results show that a total of 44 O&M interventions were observed across all 16 participants in the pre case, 30 at the SS-ONLY, and 14 at the SS+FB crosswalk. On average, each participant experienced 1.9 interventions at the SS_ONLY

Exhibit 9. Latency and yield lost time statistics for CTL crosswalks.

a) Latency (s)

Pre		Avg.	Min.	Max.	Std. Dev.
	SS-ONLY (n = 16)	8.2	2.1	15.9	3.8
	SS+FB (n = 16)	10.0	3.1	32.0	7.0
Post					
	SS-ONLY (n = 14)	7.6	2.2	12.5	2.9
	SS+FB (n = 14)	6.8	1.7	11.8	2.5

b) Yield Lost Time (s)

Pre		Avg.	Min.	Max.	Std. Dev.
	SS-ONLY (n = 16)	3.6	–0.9	13.7	3.7
	SS+FB (n = 16)	3.4	–5.1	18.3	5.1
Post					
	SS-ONLY (n = 14)	4.1	0.5	13.0	3.9
	SS+FB (n = 14)	3.8	1.1	9.6	2.3

Exhibit 10. O&M intervention statistics for CTL crosswalks.

	Intervention Rate			
Pre	**Avg.**	**Min.**	**Max.**	**Std. Dev.**
SS-ONLY (n = 16)	9.4%	0.0%	30.0%	9.5%
SS+FB (n = 16)	5.6%	0.0%	15.0%	5.2%
Post				
SS-ONLY (n = 14)	2.9%	0.0%	15.0%	4.7%
SS+FB (n = 14)	1.4%	0.0%	10.0%	3.1%

crosswalk in the pre condition, which corresponds to 9.4% of crossing attempts. At the SS+FB crosswalk in the pre condition, the average rate of interventions was 0.9 interventions per participant, which equates to 5.6% of crossing attempts, as shown in Exhibit 10. These rates are much higher than for other observed sites and indicate a lot of risk at this crossing. While some pedestrians didn't experience any interventions, others had up to six interventions out of 20 crossings at the SS-ONLY crosswalk, resulting in an intervention rate of 30%. While fewer average interventions were observed at the SS+FB crosswalk compared to SS-ONLY, the difference is not statistically significant ($p = 0.1614$).

The installation of treatments reduced interventions significantly at both crosswalks to 2.9% and 1.4% at the SS-ONLY and SS+FB corners, respectively ($p = 0.0204$ and $p = 0.0112$). This suggests that while the treatments didn't have a huge effect on crossing performance in terms of opportunity utilization and mixed results on delay, the impact on interventions seems clear and noteworthy for both crosswalks.

While the effect of the treatments on the reduction of interventions is significant, crossing risk still remains. Ashmead et al. (2005) posited that the probability of a dangerous crossing decision is given by $1-(1-p_{\text{per crossing}})^n$, where $p_{\text{per crossing}}$ is the observed intervention rate and n the number of crossing attempts. After 40 crossings (twice per day, 5 days a week, over 4 weeks), the probabilities of a risky decision at the rates of 1.4% and 2.9% are 43.1% and 69.2%, respectively. After 100 crossings, the post intervention rate of 2.9% at the SS-ONLY crosswalk results in a 94.7% likelihood of a risky decision.

Exhibit 11 explores the hypothesis that the intervention rate was related to the time of day that the subjects participated in the study. Members of the research team anecdotally found the p.m. periods at the SS-ONLY corner very difficult to cross due to high afternoon turning volumes in the channelized turn lane. The exhibit further provides insight in the variability of interventions across participants. Note that participants 5 and 14 did not participate into the post study. Their post intervention rates are shown in the negative to distinguish them from participants with zero interventions. Given the intervention patterns, the hypothesis that the higher volume resulted in a greater degree of risk could not be supported. The figures further illustrate that the degree of risk varies across participants, even after controlling for time of day.

Channelized Turn Lane Results Summary

The field evaluation at the channelized turn lane in Charlotte showed that participants experienced a lot of delay and risk at this site. Despite the fact that only a single lane needed to be crossed, the combination of background noise at the busy

Exhibit 11. Intervention statistics by subject and time of day.

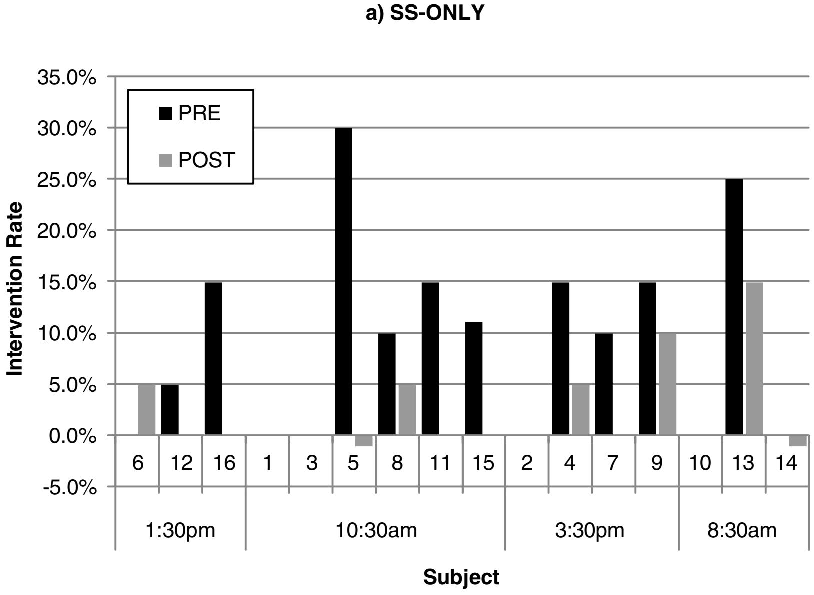
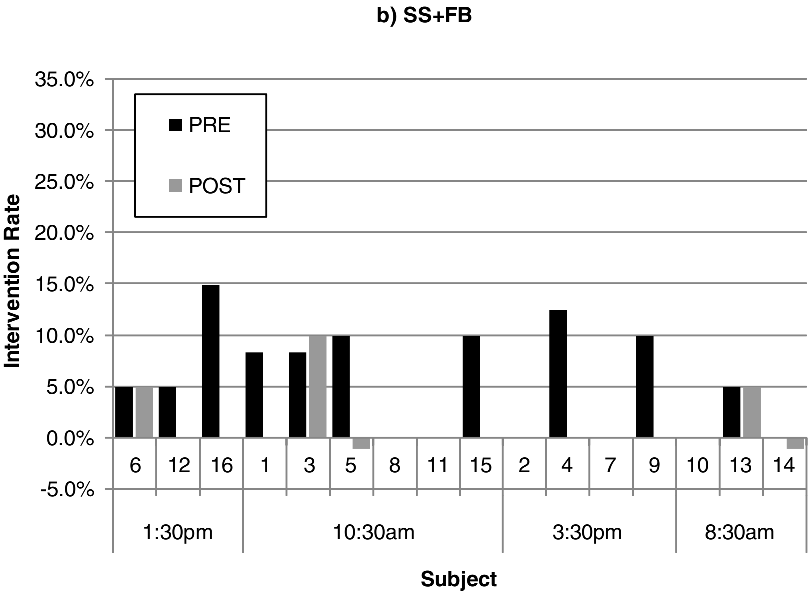

a) SS-ONLY

Exhibit 11. (Continued).



intersection and fast approach speeds in the turn lane caused higher delays and more frequent interventions than at the roundabout sites, including the two-lane roundabout in Golden. Exhibit 12 summarizes the crossing performance for the CTL location.

The installation of the sound strip and lane delineator treatments at the SS-ONLY corner did not have a large impact on most of the availability and utilization performance measures when aggregated for all participants. However, individual participants seemed to benefit from the treatments, and the treatments further resulted in a significant reduction in interventions.

Exhibit 12. Crossing performance summary pre and post at channelized turn lane.

	SS-ONLY Turn Lane		SS+FB Turn Lane	
Performance Measure	**Pre**	**Post**	**Pre**	**Post**
Yield Availability	18.4%	18.6%	15.2%	22.0%
Gap Availability	34.9%	41.2%	44.7%	49.2%
Yield Utilization	50.8%	40.5%	53.1%	64.6%
Gap Utilization	60.3%	68.2%	63.2%	89.3%
85th percentile Delay (s)	40.9	32.7	38.6	17.9
O&M Interventions	9.4%	5.6%	2.9%	1.4%

PART 2

Detailed Single-Lane Roundabout: Golden, CO

Introduction

This section describes detailed analysis results of data collected at the single-lane roundabout in Golden, CO, at the intersection of Golden Road and Ulysses Road (Exhibit 13). The initial focus is on pedestrian-related measures, including the availability and utilization of yield and gaps, as well as pedestrian delay and O&M interventions.

The single-lane roundabout was studied twice, coinciding with the pre and post studies at the nearby two-lane roundabout. But contrary to that site, no pedestrian crossing treatments were installed at this single-lane roundabout. Without treatment installation, the pre–post comparison serves as a control for any learning effects or changes in driver behavior between the two studies. The analysis presents findings in the pre and post conditions for the studied crosswalk sequentially. Only the eastern crosswalk was included in the study. The results are also compared to those gathered at other single-lane roundabouts included in this study.

The pre study was completed in July 2008 and had a total of 18 blind travelers. Thirteen of the original 18 participants returned for the post experiment in September 2008. Again, no treatments were installed at this roundabout, so the underlying hypothesis is that overall performance in pre and post conditions are the same.

Golden Single-Lane Analysis Results

Site Description

A picture of the studied crosswalk is shown in Exhibit 14. The roundabout has a central island diameter of 100 ft, including a 10-ft truck apron. The lanes at the studied crosswalk are 20 ft wide, partly to accommodate a nearby roadside bus stop. The crosswalk is located approximately 60 ft from the circulating lane measured at the exit side, and approximately 50 ft from the roundabout yield line at the entry. The two-stage crossing is divided by an 8-ft raised splitter island, but the crossing itself is at pavement elevation. No pedestrian-detectable warning surfaces were installed on the splitter island and so the study participants were instructed by the O&M specialist when they completed the first half of the crossing. Detectable warnings were installed on the outside curb ramps, and the crosswalk was outfitted with standard pedestrian signage.

Crossing Statistics for Crosswalk

The analysis of crossing performance focuses on aspects of pedestrian–vehicle interaction following the NCHRP Project 3-78A analysis framework. The first analysis component describes the availability and utilization of yields in both the pre and post treatment conditions. Two yield measures are used in the analysis:

- **P(Y_ENC):** The probability of encountering a yield event, defined as the number of yields divided by the total of all events encountered by the pedestrian until he/she completes the crossing.
- **P(GO|Y):** The probability of yield utilization, defined by the number of crossings in a yield divided by total number of yields encountered by the pedestrian.

The P(Y_ENC) measure is somewhat different from the traditionally used probability of yielding, since it is calculated on the basis of all pedestrian–vehicle events and not just potential yielders. Chapter 3 provides additional discussion on these and other performance measures, including examples on the difference between the yielding measures.

Exhibit 15 shows the statistics for the studied crosswalk. The figures shown represent the mean results by crossing leg considering all subjects. Each subject completed four crossing *trials* at the roundabout, with each trial consisting of four *lane* crossings (e.g., entry–exit–exit–entry). For example, a subject in the pre condition would have crossed the entry and exit portions of the crosswalk, respectively, eight times (twice in

Exhibit 13. Aerial view of roundabout.

Photo by Google

Exhibit 15. Yield availability and utilization statistics for studied crosswalk.

a) P(Y_ENC)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	51.1%	16.7%	100.0%	18.4%
Exit	29.6%	7.1%	57.1%	13.7%
Overall	40.4%	7.1%	100.0%	19.4%
Post (n = 13)				
Entry	51.1%	18.8%	100.0%	21.1%
Exit	36.5%	13.6%	62.5%	16.5%
Overall	43.8%	13.6%	100.0%	20.0%

b) P(GO|Y)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	82.8%	36.4%	100.0%	20.1%
Exit	76.0%	25.0%	100.0%	26.1%
Overall	79.4%	25.0%	100.0%	23.2%
Post (n = 13)				
Entry	80.3%	21.3%	100.0%	23.3%
Exit	89.2%	66.7%	100.0%	12.7%
Overall	84.7%	23.1%	100.0%	18.9%

each of four trials). The average performance for the entry leg in the pre condition is then calculated from the mean of these eight crossings for all 18 subjects. The overall average is then calculated from 36 observations (18 entry and 18 exit) each representing eight individual crossing attempts. In the post conditions, 13 subjects participated in the experiment. In total, 31 subjects were included in the study (18 pre, 13 post) and each performed 16 lane crossings (four trials at four lanes each), resulting in a total of 496 crossing attempts at this location.

Exhibit 15 shows that the probability of encountering a yield, P(Y_ENC), was higher in the entry lane than in the exit lane for both the pre ($p = 0.0004$) and post ($p = 0.0624$) conditions. The yield encounter probability did not change significantly in the pre and post studies, suggesting that driver behavior was comparable between the two studies.

Exhibit 14. The studied crosswalk.

Photo by Janet Barlow

The exhibit further shows the rates of yield utilization, P(GO|Y), defined as the rate of yields that resulted in a pedestrian crossing the roadway. The yield utilization rates are generally on the order of 75% to 90%, and no significant differences were observed in either the pre–post or entry–exit comparisons due to large standard deviations in the mean estimates.

A considerable fraction of yields further fell into the "forced yield" category, which is defined as the pedestrian stepping out into the roadway before the vehicle initiated the yielding process. The degree of risk associated with these events depends on the relative position and speed of the vehicle at the time of crossing initiation. Forced yield events should therefore not necessarily be interpreted as poor or risky decisions. In the pre condition, 32.5% and 40.6% of yields were forced at the entry and exit leg, respectively. In the post condition, the corresponding forced yield percentages were 22.2% and 39.4%. The differences between pre and post percentages of forced yields are not statistically significant ($p = 0.2294$ and $p = 0.8955$ for entry and exit, respectively). The exit leg crossing did show a greater percentage of forced yields for both pre and post conditions, but these differences were also not statistically significant.

The analysis next considered the availability and utilization of crossable gaps. For the purpose of this analysis, a crossable gap was defined as a gap greater than 8 s which was sufficient to cross the wide 21-ft crosswalk at a walking speed of 3.5 ft/s, while allowing for a 2-s safety buffer. This 2 s allows for some pedestrian reaction time before initiating the crossing, as well as a safety buffer between a completed crossing and the next vehicle arrival. Similar to the yield statistics, two gap-related parameters are defined:

- **P(CG_ENC):** The probability of encountering a CG event (gap greater than 8 s), defined as the number of crossable gaps divided by the total of all events encountered by the pedestrian.
- **P(GO|CG):** The probability of crossable gap utilization, defined by the number of crossings in a CG divided by total number of CGs encountered by the pedestrian.

Exhibit 16 shows the statistics for the studied crosswalk.

The results in Exhibit 16 show that the P(CG_ENC) is slightly higher on the entry leg for the pre conditions, but this difference is not significant at $p = 0.1125$. There is no significant effect of P(CG_ENC) in a pre–post comparison, suggesting that traffic patterns with respect to gap availability remained largely unchanged between the two studies.

Exhibit 16 further shows that the blind study participants generally had high crossable gap utilization rates, averaging in the 80% to 90% range. This may be the result of a very conservative crossable gap definition that allows most pedestrians to cross. In fact, some assertive pedestrians crossed in gaps smaller than this threshold, resulting in P(GO|Gap>Min) values greater than 100% (capped in Exhibit 16). No significant difference in P(GO|CG) is detected in a pre–post or entry–exit comparison.

Exhibit 16. Crossable gap availability and utilization statistics for studied crosswalk.

a) P(CG_ENC)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	26.3%	0.0%	44.4%	12.4%
Exit	20.6%	4.8%	34.8%	8.4%
Overall	23.5%	0.0%	44.4%	10.8%
Post (n = 13)				
Entry	21.5%	0.0%	37.5%	9.4%
Exit	21.1%	8.3%	50.0%	11.3%
Overall	21.3%	0.0%	50.0%	10.2%

b) P(GO|CG)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	83.2%	33.3%	100.0%*	23.7%
Exit	86.8%	40.0%	100.0%*	23.4%
Overall	85.1%	33.3%	100.0%*	23.2%
Post (n = 13)				
Entry	80.9%	45.5%	100.0%	22.3%
Exit	81.4%	40.0%	100.0%	22.5%
Overall	81.2%	40.0%	100.0%	21.9%

* These figures were capped at 100%, although the calculation resulted in estimates greater than 100%. This occurs if pedestrians utilize some non-crossable gaps and therefore have more utilized gaps than there are crossable gaps available.

The combined effect of gap and yield availability and utilization is reflected in the delay experienced by pedestrians. Delay statistics in Exhibit 17 are provided for two delay measures:

- **Observed Delay per Leg (s):** The average pedestrian delay in seconds, defined as the time difference between when the trial started and when the pedestrian initiated the crossing.
- **Delay>Min (s):** The delay beyond the first opportunity (Delay>Min), defined as the time difference between first yield or crossable gap encountered by the pedestrian and the actual crossing initiation.

Statistics for all measures are for crossing one leg of the roundabout at either the exit or entry approach. The total average delay by crossing can be calculated by summing delay statistics for the entry and exit legs.

Exhibit 17 shows that small differences in average pedestrian delay per leg were observed in an entry–exit leg comparison, although none of the small differences were statistically significant at the given sample size (all $p > 0.40$). Also, no significant differences in delay were observed in a pre–post comparison (all $p > 0.50$). In addition to the average delay for all participants, it is important to emphasize that some participants experienced much larger delays. The longest overall average delay by a participant was 51.4 s per leg. A 2-min time-out was used for all trials, but none of the participants ever reached that limit at this site.

The results for Delay>Min also show no significant difference between for pre–post and entry–exit comparisons. Overall, the Delay>Min results suggest that the blind pedestrians did not

Exhibit 17. Average pedestrian delay statistics for studied crosswalk.

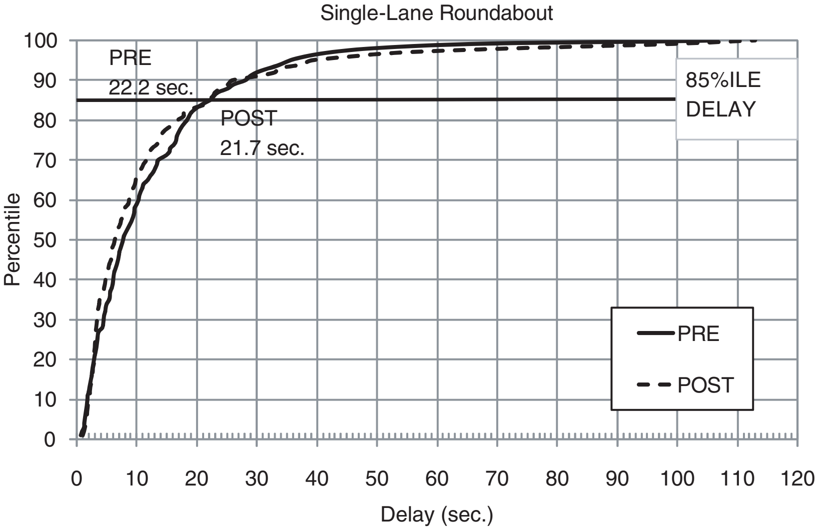
a) Observed Delay per Leg (s)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	10.9	4.0	31.3	7.3
Exit	13.0	3.5	29.4	7.9
Overall	11.9	3.5	31.3	7.6
Post (n = 13)				
Entry	13.3	2.7	51.4	13.6
Exit	11.0	3.4	27.8	7.3
Overall	12.1	2.7	51.4	10.7

b) Delay>Min (s)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	2.8	0.1	6.5	2.1
Exit	2.7	0.1	7.0	2.3
Overall	2.8	0.1	7.0	2.2
Post (n = 13)				
Entry	3.7	0.3	19.9	5.2
Exit	2.5	0.1	9.9	2.8
Overall	3.1	0.1	19.9	4.2

Exhibit 18. Delay distribution all subjects – single-lane roundabout.

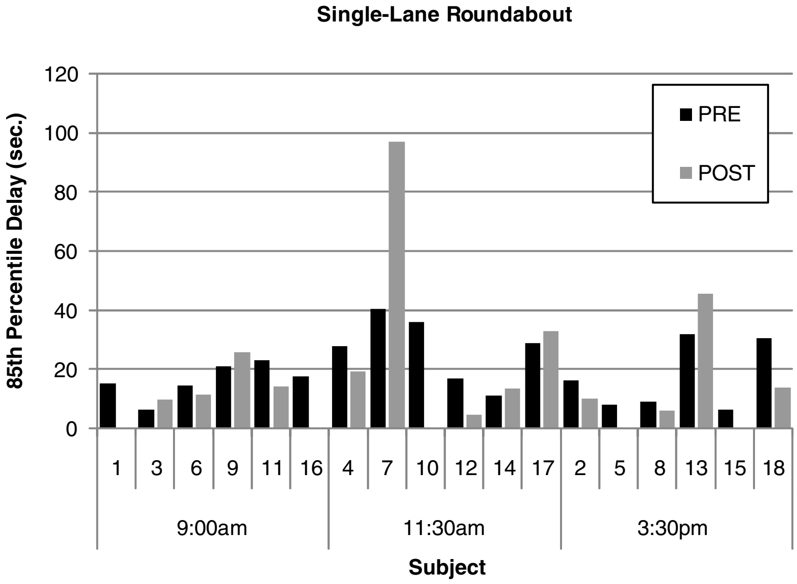


miss a lot of crossing opportunities. Despite these low averages, some pedestrians experienced Delay>Min up to 19.9 s. The null hypothesis that Delay>Min = 0 is rejected for both pre and post conditions ($p < 0.0001$ and $p = 0.0030$, respectively).

Exhibit 18 shows the distribution of delay for all subjects in the pre and post conditions. The hypothesis that no significant changes took place between the studies is supported by the data. This implies that any effects observed at the neighboring two-lane roundabout are likely attributable to the installation of the treatments and not a learning effect by pedestrians. Exhibit 19 shows the 85th percentile delay estimate by subject. It appears that one participant (subject 7) experienced significantly greater delay in the post condition, while all other delay performances remained largely unchanged. The delay statistics are arranged by time of day during which subjects participated, but no trends can be identified. Note that subjects 1, 5, 10, 15, and 16 did not participate in the post study.

The analysis further investigated two new parameters that were not previously used in Schroeder, Rouphail, and Hughes (2009). Both measures are intended to describe the efficiency

Exhibit 19. 85th percentile delay by subject – single-lane roundabout.



with which a crossing opportunity is utilized for both gaps and yields:

- **Latency (s):** Latency is defined as the time between when the last vehicle went through the crosswalk and the time the pedestrian initiated the crossing.
- **Yield Lost Time (s):** The YLT is defined as the time between when a driver first yields and the time the crossing is initiated. Note that in some cases, pedestrians may prefer to cross only after a car has come to a full stop (stopped yield), and so some inherent yield utilization time is expected.

Exhibit 20 shows statistics for both measures.

The latency results in Exhibit 20 suggest that on average pedestrians wait 4 to 6 s into a crossable gap before initiating the crossing, suggesting inefficiency in decision-making. No significant difference in latency was detected for a pre–post or entry–exit comparison.

For the yield lost time measure, pedestrians on average wait 1.5 to 2 s before crossing in front of a yielding vehicle. The average maximum YLT was 11.1 s for the pre and 6.6 s for the post condition. Note that in many cases, drivers will not be willing to wait this long and a high YLT will therefore translate to an increased percentage of missed yields [lower $P(GO|Y)$]. Also note that some YLT values are negative, suggesting that some pedestrians forced vehicles to yield.

Finally, the analysis includes the rate of O&M interventions that represent a measure of pedestrian risk during the crossings. The study participants were at all times accompanied by a certified O&M specialist who was directed to stop the participants if the crossing decision would have resulted in undue risk to pedestrian and/or driver. The resulting rate of O&M intervention is defined as follows:

- **Intervention Rate (%):** The intervention rate is defined by the number of times the O&M specialist intervened for a particular subject divided by the total number of lanes crossed for a particular condition. For example, one intervention over a set of eight lane crossings at the roundabout entry corresponds to an intervention rate of 12.5%.

Exhibit 20. Latency and yield lost time statistics for studied crosswalk.

a) Latency (s)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	5.7	1.8	16.0	4.0
Exit	4.9	2.4	10.5	1.9
Overall	5.3	1.8	16.0	3.0
Post (n = 13)				
Entry	5.0	1.3	12.6	3.1
Exit	4.7	2.7	7.3	1.6
Overall	4.8	1.3	12.6	2.4

b) Yield Lost Time (s)

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	2.6	–2.1	11.1	3.8
Exit	0.5	–1.9	5.1	2.0
Overall	1.6	–2.1	11.1	3.2
Post (n = 13)				
Entry	2.8	0.1	6.6	2.3
Exit	1.1	–1.4	4.4	1.8
Overall	1.9	–1.4	6.6	2.2

The summary statistics for O&M Interventions are given in Exhibit 21.

The results show that a total of four O&M interventions were observed in the pre case over a total of 72 lane crossings at the entry leg for a rate of 2.8%. In the post analysis the intervention rate at the entry was 1.0%; however, due to high standard deviations that difference is not significant ($p = 0.2616$) at this sample size. No interventions were observed at the exit leg of this particular roundabout. The overall intervention rates for pre and post were 1.4% and 0.5%, respectively. Again, this difference is not statistically significant. The null hypothesis that the intervention rate is zero is rejected for the pre condition ($p = 0.0344$) but cannot be rejected at the given sample size for the post evaluation.

Exhibit 22 explores the distribution of interventions by subject and time of day. Given the rare occurrence of interventions, it is difficult to draw any conclusions about patterns at the given sample size. Participants who didn't return for the post study are shown with negative intervention rates to visually distinguish them from zero-intervention subjects. The numbers are shown as the percentage of interventions from 16 lane crossing per subject at this site.

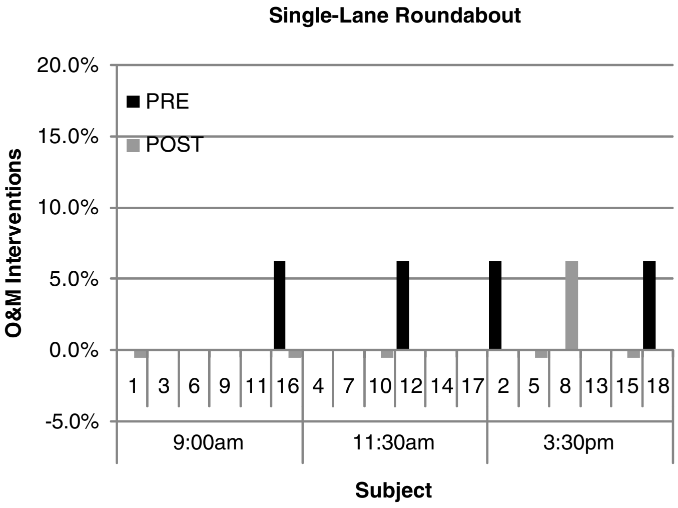
While the rates of interventions appear low, this does not mean that a crossing is safe. Ashmead et al. (2005) posited that the probability of a dangerous crossing decision is given by $1-(1-p_{\text{per crossing}})^n$, where $p_{\text{per crossing}}$ is the observed intervention rate and n the number of crossing attempts. After 40 crossings (twice per day, 5 days a week, over 4 weeks), the probabilities

Exhibit 21. O&M intervention statistics for single-lane roundabout crosswalk.

Intervention Rate

Pre (n = 18)	Avg.	Min.	Max.	Std. Dev.
Entry	2.8%	0.0%	12.5%	5.3%
Exit	0.0%	0.0%	0.0%	0.0%
Overall	1.4%	0.0%	6.3%	2.7%
Post (n = 13)				
Entry	1.0%	0.0%	12.5%	3.5%
Exit	0.0%	0.0%	0.0%	0.0%
Overall	0.5%	0.0%	6.3%	1.7%

Exhibit 22. O&M interventions by subject and by time of day.



of a risky decision at the rates 0.5% and 1.4% are 18.2% and 43.1%, respectively. After 100 crossings, the entry intervention rate of 2.8% in the pre condition results in a 94.2% likelihood of a risky decision.

Golden, CO, Single-Lane Roundabout Summary

The field evaluation at the single-lane roundabout in Golden did not provide statistical evidence of a learning effect by the blind study participants or significant changes in driver behavior or traffic volumes. The crossing opportunity availability measures, P(CG_ENC) and P(Y_ENC), remained unchanged, as did the rate of utilization of these opportunities. The analysis of the delay performance of study participants showed no conclusive pre and post difference. The number of experimenter interventions appeared to have dropped from four in the pre to only one intervention in the post; however, due to the low sample size and rare occurrence of this measure, this effect is believed to be due to random variability. Exhibit 23 summarizes the crossing performance for the Golden single-lane roundabout.

Exhibit 23. Crossing performance summary pre and post at single-lane roundabout.

Performance Measure	Pre	Post
Yield Availability	40.4%	43.8%
Gap Availability	23.5%	21.3%
Yield Utilization	79.4%	84.7%
Gap Utilization	85.1%	81.2%
85th percentile Delay (s)	22.2	21.7
O&M interventions	1.4%	0.5%

In a comparison to other single-lane roundabouts, the Golden roundabout showed a higher rate of driver yielding and a comparable rate of crossable gap occurrence. The rate of opportunity utilization was in the same general range as other sites. For all compared sites, the between-subject variability was very large.

PART 3

Detailed Single-Lane Roundabout: North Carolina

Introduction

This section describes detailed analysis results of data collected at two single-lane roundabouts in North Carolina. The analysis and comparison of these two sites were previously published in Schroeder, Rouphail, and Hughes (2009), although the present document shows some revised variable definitions compared to the published paper. The first roundabout is located at the intersection of 9th Street and Davidson Avenue in Charlotte. This roundabout was included in the original data collection scope of NCHRP Project 3-78A and was initially proposed to be evaluated in a pre and post experiment with treatment installation. However, the treatment installation and post study were aborted later in the project and funds reallocated to other purposes. One of the uses of these funds was the evaluation of the second single-lane roundabout described in this document. The roundabout at the intersection of Pullen Road and Stinson Drive in Raleigh was previously studied in a related project, using the same experimental protocol applied in NCHRP Project 3-78A. The analysis presented in this document was performed from video observations of that study. Another use of the funds was data collection at a single-lane roundabout in Golden, which is discussed in a separate document.

The original data collection scope for NCHRP Project 3-78A included the evaluation of one single-lane roundabout at the intersection of 9th Street and Davidson Avenue in Charlotte (Site DAV-CLT). In the discussion at the interim NCHRP Project 3-78A panel meeting in January 2008 in Washington, D.C., concerns were raised that the low traffic volumes at this site were not representative of a typical single-lane U.S. roundabout. As a result, the site was deemed to be accessible and would not substantively benefit from the installation of the proposed treatments. The NCHRP Project 3-78A team thus agreed to compare the crossing performance statistics to a higher-volume single-lane roundabout and contrast the accessibility criteria, which is the focus of this document.

Several members of the research team are also involved in a separate research effort under sponsorship of the NIH. In this multi-year NIH project, research on the general crossing performance of blind pedestrians is performed, and a subset of studies focuses on roundabouts. In particular, a study in the fall of 2004 investigated the feasibility of an automated yield-detection system (AYDS) at a single lane roundabout at Pullen Road and Stinson Drive in Raleigh (Site PS-RAL). The data collection protocol at the PS-RAL study was comparable to DAV-CLT and included trials in both conditions with the AYDS treatment "on" and "off." In this document, the PS-RAL trials conducted in the "off" condition are compared to the data in the "before" study at DAV-CLT.

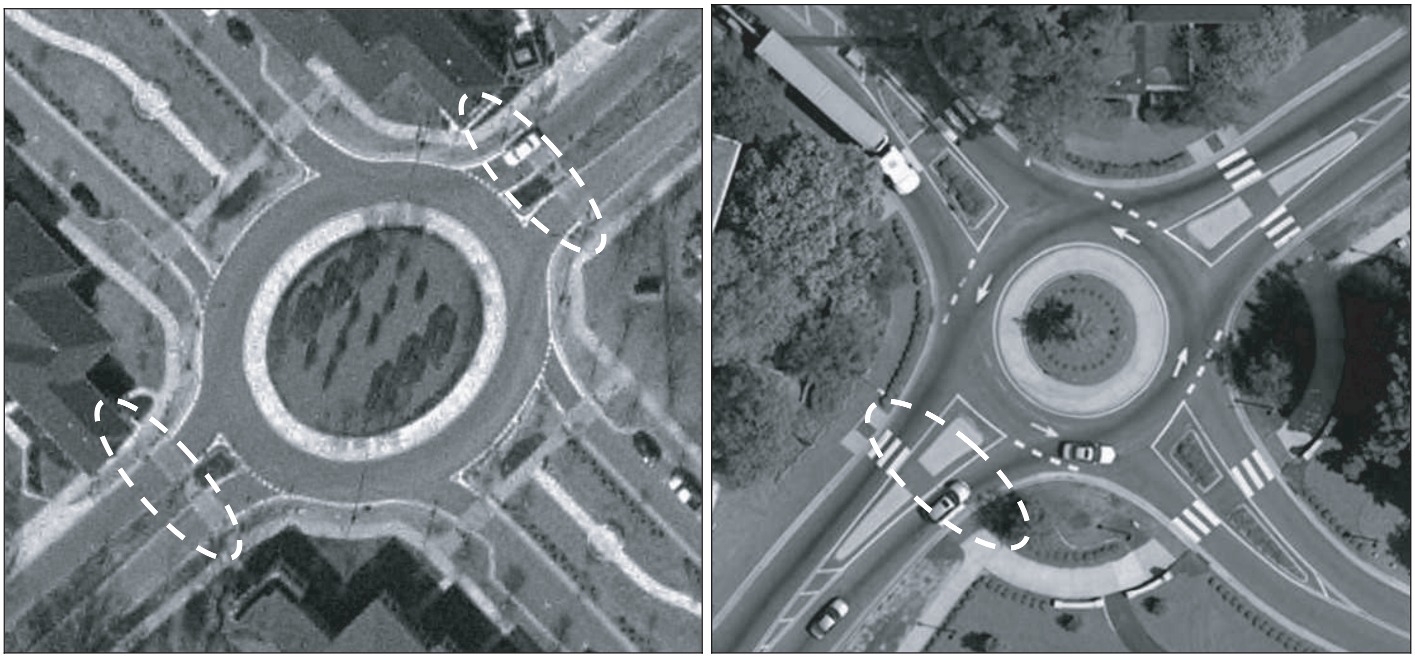
In the data collection at DAV-CLT, data from a total of 10 blind subjects were analyzed. The dataset for PS-RAL resulted in usable data from 12 blind participants as well as six sighted comparison subjects (not shown). At both sites, a full crossing consisted of four lane crossings (for example entry–exit–exit–entry) with the starting order of lanes randomized for each subject. At DAV-CLT each subject completed three full crossings at the northern and three full crossings at the southern crosswalk, resulting in a total of 12 entry and 12 exit individual lane crossings. At the PS-RAL site each subject completed eight full trials at one crosswalk, resulting in 16 entry and 16 exit lane crossings.

North Carolina Single-Lane Analysis Results

Site Description

The DAV-CLT roundabout has an inscribed diameter of approximately 140 ft and approach speed limits of 25 mph. The PS-RBT has a smaller inscribed diameter of 88 ft and also has approach speed limits of 25 mph. Exhibit 24 below shows aerial views of both sites. The tested crosswalks are highlighted.

Exhibit 24. Aerial views of DAV-CLT and PS-RAL roundabouts.



a) DAV-CLT

b) PS-RAL

When traffic volumes are compared, the major approaches on Davidson Avenue and Pullen Road have AADTs of about 9,900 and 15,000, respectively. The side streets on 9th Street and Stinson Drive respectively have much lower volumes. Exhibit 25 shows the peak hour entering volumes for both sites.

The data suggest that the a.m. and p.m. peak hour volumes at the PS-RAL are about 50% and 90% higher than at the DAV-CLT site, respectively. More importantly, the lunch peak hour at PS-RAL has 240% more traffic, which is mostly a result of generally low daytime volumes at the DAV-CLT site. A similar trend was observed during the actual experimental trials. While the DAV-CLT has medium traffic volumes in the a.m. and p.m. peak hours, traffic during the actual experimental trials, which were carried out more often slightly outside the peak hours, was relatively low.

The research team also gathered sample speed observations at both sites. The approach speeds on the entry approach lanes to the north and south crosswalk at the DAV-CLT site were 27.6 and 26.0 mph, respectively. Upon entry, the average vehicle speed dropped to approximately 17.6 mph due to the roundabout geometry. The average approach speed at the southern crosswalk of the PS-RAL roundabout was lower than at DAV-CLT at 22.8 mph. The average entering speed to the PS-RAL roundabout was 15.6 mph. The average exiting speeds at DAV-CLT and PS-RAL were approximately 17.3 and 15.3 mph, respectively. The lower speeds at PS-RAL are likely

Exhibit 25. Peak hour entering volumes for sites.

a) PS-RAL

	Peak Hour Volumes Total Entering Volumes, Sep-2007				
PS-RAL	**North**	**East**	**South**	**West**	**TOTAL**
AM Peak (7:30-8:30AM)	779	3	461	36	1279
Lunch Peak (12:15-1:15PM)	583	38	560	113	1294
PM Peak (5:00-6:00PM)	454	20	887	123	1484

b) DAV-CLT

	Peak Hour Volumes Total Entering Volumes, Nov-2007				
DAV-CLT	**North**	**East**	**South**	**West**	**TOTAL**
AM Peak (7:30-8:30AM)	157	79	506	92	834
Lunch Peak (1:00-2:00PM)	198	26	272	39	535
PM Peak (5:00-6:00PM)	364	70	277	76	787

attributable to the smaller inscribed diameter and associated lower design speed of the roundabout.

Crossing Statistics

The analysis of crossing performance focuses on aspects of pedestrian–vehicle interaction following the NCHRP Project 3-78A analysis framework. The first analysis component describes the availability and utilization of yields in both the pre and post treatment conditions. Two yield measures are used in the analysis:

- **P(Y_ENC):** The probability of encountering a yield event, defined as the number of yields divided by the total of all events encountered by the pedestrian until he/she completes the crossing.
- **P(GO|Y):** The probability of yield utilization, defined as the number of crossings in a yield divided by total number of yields encountered by the pedestrian.

The P(Y_ENC) measure is somewhat different than the traditionally used probability of yielding, since it is calculated on the basis of all pedestrian–vehicle events and not just potential yielders. Chapter 3 provides additional discussion on these and other performance measures, including examples on the difference between the yielding measures.

Exhibit 26a compares the yield encounters for the two sites. It shows generally higher probabilities of encountering a yield at the PS-RAL roundabout, which may be related to the proximity to a major college campus. The PS-RAL site further suggests lower yielding at the roundabout exit leg, which is not evident at DAV-CLT.

Exhibit 26b shows the yield utilization rates at the two sites. A lower yield utilization rate is evident at DAV-CLT (67.4%) than at PS-RAL (85.4%). Both sites suggest a slightly higher yield utilization rate at the exit leg. By combining yielding and yield utilization rates, it can be stated that the PS-RAL site exhibits a higher likelihood of crossing in a yield than DAV-CLT. The range of observed yield utilization points to differences in crossing abilities among participants, with some utilizing 100% of yields while others don't utilize any.

The analysis next considered the availability and utilization of crossable gaps. For the purpose of this analysis, a crossable gap is defined as a gap that was sufficient to cross the width of the crosswalk at a walking speed of 3.5 ft/s, while allowing for a 2-s safety buffer. This 2 s allows for some pedestrian reaction time before initiating the crossing, as well as a safety buffer between a completed crossing and the next vehicle arrival. The resulting crossable gap thresholds for DAV-CLT and PS-RAL were 7 s and 6 s, respectively. Similar to the yield statistics, two gap-related parameters are defined:

- **P(CG_ENC):** The probability of encountering a CG event (gap greater than CG threshold), defined as the number of crossable gaps divided by the total of all events encountered by the pedestrian.

Exhibit 26. Yield encounters and utilization statistics for studied crosswalk.

a) P(Y_ENC)

DAV-CLT	Avg.	Min.	Max.	Std. Dev.
Entry	5.8%	0.0%	14.3%	4.8%
Exit	6.7%	0.0%	20.0%	5.0%
Overall	6.3%	0.0%	20.0%	4.9%
PS-RAL				
Entry	37.9%	13.1%	66.7%	17.8%
Exit	28.1%	8.1%	58.3%	14.4%
Overall	33.0%	8.1%	66.7%	16.6%

b) P(GO|Y)

DAV-CLT	Avg.	Min.	Max.	Std. Dev.
Entry	64.1%	0.0%	100.0%	41.2%
Exit	70.4%	0.0%	100.0%	44.1%
Overall	67.4%	0.0%	100.0%	42.3%
PS-RAL				
Entry	83.0%	50.0%	100.0%	20.4%
Exit	87.8%	60.0%	100.0%	14.1%
Overall	85.4%	50.0%	100.0%	17.3%

Exhibit 27. Crossable gap encounters and utilization statistics for studied crosswalk.

a) P(CG_ENC)

DAV-CLT		Avg.	Min.	Max.	Std. Dev.
	Entry	29.8%	18.5%	44.7%	6.9%
	Exit	27.8%	9.1%	40.0%	6.7%
	Overall	28.8%	9.1%	44.7%	6.8%
PS-RAL					
	Entry	17.7%	0.0%	30.0%	8.9%
	Exit	20.5%	0.0%	32.0%	9.7%
	Overall	19.1%	0.0%	32.0%	9.2%

b) P(GO|Gap>Min)

DAV-CLT		Avg.	Min.	Max.	Std. Dev.
	Entry	66.3%	25.0%	100.0%	20.6%
	Exit	60.3%	33.3%	100.0%	17.9%
	Overall	63.3%	25.0%	100.0%	19.3%
PS-RAL					
	Entry	52.0%	0.0%	100.0%	41.3%
	Exit	63.6%	18.8%	100.0%	26.6%
	Overall	57.8%	0.0%	100.0%	34.4%

Exhibit 28. Average pedestrian delay statistics for studied crosswalk.

a) Observed Delay per Leg (s)

DAV-CLT		Avg.	Min.	Max.	Std. Dev.
	Entry	26.6	11.2	74.0	17.0
	Exit	24.0	11.4	41.8	9.7
	Overall	25.3	11.2	74.0	13.8
PS-RAL					
	Entry	10.5	4.1	34.2	8.9
	Exit	11.6	5.2	26.7	6.8
	Overall	11.1	4.1	34.2	7.8

b) Delay>Min (s)

DAV-CLT		Avg.	Min.	Max.	Std. Dev.
	Entry	18.8	4.8	59.4	15.5
	Exit	17.2	5.2	35.1	9.6
	Overall	18.0	4.8	59.4	12.8
PS-RAL (Min = 6 s)					
	Entry	5.6	0.8	24.7	7.2
	Exit	6.1	0.8	19.4	5.8
	Overall	5.8	0.8	24.7	6.4

- **P(GO|CG):** The probability of crossable gap utilization, defined as the number of crossings in a CG divided by total number of CGs encountered by the pedestrian.

Exhibit 27 shows the statistics for the studied crosswalks.

Exhibit 27a shows the encounters of crossable gaps at the two sites. Following the definition above, the minimum crossable gaps for DAV-CLT and PS-RAL are approximately 7.0 and 6.0 s, respectively. The table shows that DAV-CLT has a slightly higher rate of gaps (28.8%) that are greater than the crossable gap than PS_RAL does (19.1%). For both sites, the gap occurrence is comparable for entry and exit legs.

Exhibit 27b shows gap utilization rates for DAV-CLT of approximately 60%. At PS-RAL the gap utilization rate is higher for the exit leg than the entry leg, with 63.6% and 52% utilization, respectively. Overall, the gap utilization rates across the two sites are comparable. Combining gap occurrence and utilization, there is a somewhat higher likelihood of crossing in a gap at DAV-CLT. The range of gap utilization again varies between 0% and 100%, emphasizing the need for a sufficient sample size given the variability of crossing behavior. In this context it is also important to point out that no utilized gaps below the defined crossable gap threshold were observed at either site, giving confidence to the assumed crossable gap thresholds.

The combined effect of gap and yield availability and utilization is reflected in the delay experienced by pedestrians. Delay statistics in Exhibit 28 are provided for two delay measures:

- **Observed Delay per Leg (s):** The average pedestrian delay in seconds, defined as the time difference between when the trial started and when the pedestrian initiated the crossing.
- **Delay>Min (s):** The delay beyond the first opportunity (Delay>Min), defined as the time difference between first yield or crossable gap encountered by the pedestrian and the actual crossing initiation.

Statistics for all measures are for crossing one leg of the roundabout at either the exit or entry approach. The total average delay by crossing can be calculated by summing delay statistics for the entry and exit legs.

Exhibit 28a compares the observed delay experienced by the blind pedestrians at both sites and suggests significantly lower delays at PS-RAL. Interpreting this difference in light of the results in Exhibits 3 and 4, the lower delay is likely attributable to greater P(Y_ENC) and greater P(GO|Y) at this site. The delay at DAV-CLT correspondingly is higher because pedestrians wait for crossable gaps in the absence of yields. The delay is comparable for the entry and exit leg at both sites. The average total delay to get across both entry and exit lanes represents the sum of the two estimates.

Exhibit 28b shows the delay beyond the first crossing opportunity for both sites. The findings are similar to those in Exhibit 28a, with pedestrians at PS-RAL experiencing less unnecessary delay compared to DAV-CLT. Again, the reason for the differences is likely related to P(Yield) and P(GO|Y). The difference in delay suggests that a crossing opportunity is utilized more quickly at PS-RAL. If these sites were analyzed using LOS definitions in the HCM, the average delay times at PS-RAL and DAV-CLT (approximately 11 and 25 s) would

Exhibit 29. O&M intervention statistics for single-lane roundabout crosswalk.

	P(Risky Crossing)			
DAV-CLT	**Avg.**	**Min.**	**Max.**	**Std. Dev.**
Entry	0.8%	0.0%	8.3%	2.6%
Exit	0.8%	0.0%	8.3%	2.6%
Overall	0.8%	0.0%	8.3%	2.6%
PS-RAL				
Entry	2.1%	0.0%	6.3%	3.1%
Exit	5.8%	0.0%	25.0%	7.3%
Overall	3.9%	0.0%	25.0%	5.8%

correspond to LOS scores C and D, respectively. To recall, the HCM defines levels of service on a scale from A (best) to F (worst) in terms of average delay per person.

Finally, the analysis includes the rate of O&M interventions that represent a measure of pedestrian risk during the crossings. The study participants were at all times accompanied by a certified O&M specialist who was directed to stop the participants if the crossing decision would have resulted in undue risk to pedestrian and/or driver. The resulting rate of O&M intervention is defined as follows.

- **Intervention Rate (%):** The intervention rate is defined by the number of times the O&M specialist intervened for a particular subject divided by the total number of lanes crossed for a particular condition. For example, one intervention over a set of eight lane crossings at the roundabout entry corresponds to an intervention rate of 12.5%.

Exhibit 29 shows the rate of experimenter interventions. The intervention rates at PS-RAL are clearly higher than DAV-CLT, and the exit lane crossing is especially risky with an intervention rate of 5.8%. At the DAV-CLT site, one participant experienced a single intervention at the entry leg and another one a single intervention at the exit leg (1 intervention in 12 crossing results in a rate of 8.3%). Since no other subjects experienced any interventions, the resulting average intervention rate across 10 subjects was 0.8% for both the entry and exit leg.

However, with repeated crossings even the 0.8% intervention rate at DAV-CLT could result in a high likelihood of a risky decision over time. Ashmead et al. (2005) discussed that the probability of a dangerous crossing decision is given by $1 - (1 - p_{\text{per crossing}})^n$, where $p_{per\ crossing}$ is the observed intervention rate and n the number of crossing attempts. Consequently, for a pedestrian who crosses this roundabout twice a day, the probability of a dangerous decision after one month (10 crossings per week over 4 weeks) is 27.5%. At the 3.9% intervention rate for PS-RAL this likelihood increases to 79.6%.

Discussion

Based on all the criteria considered in the comparison of the two sites, the higher-volume PS-RAL site is in fact *more accessible* than the DAV-CLT site *from a delay perspective*. This is primarily due to the high frequency of yields at the PS-RAL site and a high yield utilization rate. As a result, blind pedestrians on average experience less than half the delay at PS-RAL compared to DAV-CLT. Similarly, the amount of unnecessary delay beyond the first crossing opportunity is about three times as high at the DAV-CLT site. These findings are somewhat surprising, given that the availability of (long) crossing gaps at the PS-RAL is less than that at DAV-CLT. The crossable gap utilization rates appear to be comparable for both sites. However, from a risk perspective, the PS-RAL clearly shows higher intervention rates and thus a more dangerous crossing situation.

In light of these findings, it is evident that the question of roundabout accessibility is complex and cannot be reduced to a simple relationship to traffic volumes. While a low-volume site may appear to be easily accessible, a higher-volume site may result in higher accessibility if associated with a higher rate of yielding that is being utilized. The greater accessibility of the PS-RAL site is attributable to higher P(Yield) and P(GO|Y) probabilities. These two factors seemed to have a significant overall impact on reduced pedestrian delay, despite the fact that the site had higher volumes and consequently a lower availability of crossable gaps, P(Gap>Min). Given the higher propensity to yield at PS-RAL, the associated higher volumes resulted in more frequent crossing opportunities per unit of time.

The analysis in this section shows that the studied higher-volume roundabout was in fact more accessible to blind pedestrians based on the multi-criteria established in this study. The hypothesis that the DAV-CLT roundabout is "*easily accessible because of low volumes*" could not be supported by the comparison data from PS-RAL. Through the comparison it has become evident that a combination of crossable gaps, yields, and utilization rates all contribute to making a site more or less accessible.

PART 4

Detailed Two-Lane Roundabout: Golden, CO – RCW

Introduction

This section describes analysis results of data collected at the RCW of the two-lane roundabout in Golden at the intersection of Golden Road and Johnson Road (Exhibit 30). The analysis focus will be on pedestrian-related measures, including the availability and utilization of yield and gaps, as well as pedestrian delay and O&M interventions. The measures are defined in the methodology chapter of this report.

Because of the two-lane approaches at this site, the section distinguishes between near-lane and far-lane effects at the crosswalk. These describe the vehicle state in the near and far lane relative to the position of the waiting pedestrian.

This section focuses on the south crosswalk with the treatment effect of the raised crosswalk. The analysis presents findings in the pre and post conditions for the studied crosswalk sequentially.

The pre study was completed in July 2008, and a total of 18 blind travelers participated in the pre study. The treatment was installed following the pre study, and 12 of the original 18 participants returned for the post experiment in September 2008.

Raised Crosswalk Evaluation

Raised Crosswalk Treatment Overview

An RCW (Exhibit 31) was installed at the southern leg of the roundabout. The treatment had the objective of slowing drivers as they traversed the crosswalk, and the research team hypothesized that the speed impediment may also result in an increased likelihood of drivers yielding. Overall, the raised crosswalk was a lower-cost treatment than the PHB but also affected drivers in the absence of pedestrians (the PHB rested in “Dark” mode).

The raised crosswalk was constructed from asphalt at a vertical elevation of 3 in. and a 1:15 slope transition from the existing pavement surface. This elevation and slope resulted in a fairly gentle transition for vehicular traffic, but was selected to mitigate concerns on the impacts on traffic flow. It is expected that a higher elevation and/or steeper transition slope would drastically alter driver behavior, and these results therefore cannot be transferred directly to raised crosswalks with different geometries.

The raised crosswalk was further installed as a temporary installation, and therefore no reconstruction was done to the curb line. Due to drainage considerations, the raised crosswalk was at road surface level on the side of the street and then sloped upward from there. For pedestrians this resulted in a somewhat uncomfortable walking experience since the crosswalk curb ramp down slope was followed by an up slope onto the raised crosswalk. For a permanent installation, it is recommended that drainage considerations be incorporated into a raised crosswalk design that is flush with the sidewalk.

Pretest Pedestrian Behavior at the RCW

The NCHRP Project 3-78A analysis of single-lane crossings used a performance evaluation framework that described the availability of crossing opportunities, the rate of utilization of these opportunities, as well as the delay and risk associated with the crossings. For a single lane, the yield and gap events are uniquely defined by the vehicle state in the conflict lane. However, at a two-lane crossing the analysis needs to consider the vehicle state in both lanes. The following analysis distinguishes between driver behavior in the near lane (the lane closest relative to the position of the pedestrian) and the far lane. Depending on the crossing location (entry/exit and curb/island) the near lane can be the inside or outside lane of the two-lane approach. The analysis defines the vehicle state in the near lane in five event categories:

1. **Rolling Yield (RY):** Pedestrian encounters a driver who has slowed down for the pedestrian, but has not come to a full stop.

Exhibit 30. Aerial view of roundabout.

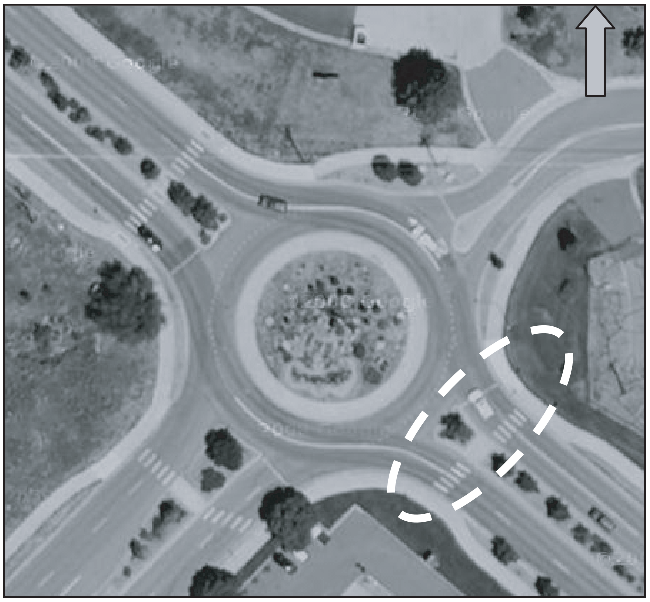


Photo by Google

2. **Stopped Yield (STY):** Pedestrian encounters a driver who has come to a stop, defined as moving at a speed less than 3 mph.
3. **Forced Yield (FY):** Pedestrian initiates crossing before the vehicle initiated the yield, but then forces the driver to slow down by entering the crosswalk.
4. **Crossable Gap (CG):** Pedestrian encounters a gap large enough to safely cross the street. A crossable gap is defined as the crossing width divided by 3.5 ft/s walking speed plus 2 s for start time and safety buffer.
5. **Non-Crossable Gap (non-CG):** Pedestrian encounters a gap between vehicles shorter than the crossable gap threshold.

Exhibit 31. Raised crosswalk.

Photo by Bastian Schroeder

The vehicle state in the far lane will be defined relative to the near-lane condition in five principal categories: rolling yield, stopped yield, crossable gap, non-crossable gap, and multiple events. The last category indicates that more than one event took place in the far lane during one near-lane event. For example, several cars could have gone through the far lane during one large gap in the near lane. For multiple events, the last event in the sequence is considered for analysis. Exhibit 32 shows the near-lane and far-lane effects for the pre condition at the RCW. The event outcomes are broken down by whether the events were utilized by the pedestrians.

The exhibit shows that 183 of 686 encountered events in the near lane (26.7%) were yields, but that only some of those events were associated with a yield or crossing opportunity in the far lane. Participants did not utilize 43 rolling yields and 40 stopped yields. The corresponding overall rate of yield utilization is 45.4%, but 16.4% of utilized yields in the near lane were forced by the pedestrian seizing the crosswalk. The analysis of the far-lane event shows that a majority of the non-utilized yields were attributable to either non-crossable gaps or multiple events in the far lane. Overall, 53.5% of yields were double yields with stopping or stopped cars in both lanes (including forced yields), of which 61.2% were utilized.

Exhibit 32. Near–far lane effects, pre condition, for RCW.

		Far-Lane Event										
							Multiple Events					
Near-Lane Event	Lane Outcome	Rolling Yield	Stopped Yield	Forced Yield	X-Able Gap	Non-X. Gap	RY	STY	CG	FY	non-CG	Total
Rolling Yield	Utilized	3	2	1	2	0	1	0	1	0	0	**10**
	Non-Utlz.	3	8	0	0	28	1	1	1	0	1	**43**
Stopped Yield	Utilized	7	22	9	17	1	2	0	2	0	0	**60**
	Non-Utlz.	1	14	0	1	18	0	3	1	0	2	**40**
Forced Yield	Utilized	2	6	3	12	2	1	0	3	1	0	**30**
	Non-Utlz.	0	0	0	0	0	0	0	0	0	0	**0**
Crossable Gap	Utilized	5	12	31	74	1	0	1	12	2	0	**138**
	Non-Utlz.	1	2	0	3	21	0	0	1	0	9	**37**
Non-Cross. Gap	Utilized	1	0	0	2	2	0	0	0	0	0	**5**
	Non-Utlz.	8	7	0	15	266	2	0	3	0	22	**323**
Total		**31**	**73**	**44**	**126**	**339**	**7**	**5**	**24**	**3**	**34**	**686**

Exhibit 33. Availability and utilization statistics for pre condition, RCW.

Pre (n = 686)	Near Lane	Far Lane
Availability Statistics		
P(Y_Enc)	26.7%	23.8%
P(CG_Enc)	25.5%	21.9%
Utilization Statistics		
P(GO|Y)	54.6%	68.7%
P(GO|CG)	78.9%	83.3%

Of a total of 503 encountered gaps in the near lane, 175 were crossable (34.8%), and 78.9% of these crossable gaps were utilized by the pedestrian. The likelihood of encountering a crossable gap from the 686 total events was 25.5%. Of the 37 non-utilized crossable gaps, 30 had non-crossable gaps in the far lane. The near–far lane evaluation makes it evident that both need to be considered in the evaluation of pedestrian behavior. Exhibit 33 shows a summary of the crossing opportunity availability and utilization statistics for the pre condition.

The exhibit shows a relatively low rate of yield and crossable gap occurrence in both lanes, explaining the large portion of pedestrian–vehicle events that did not result in a crossing. Further, the rate of yield utilization is only 54.6% and 68.7% in the near and far lane, suggesting a lot of pedestrian uncertainty. Gap utilization is somewhat higher, at around 80%.

The results in Exhibit 33 can further be interpreted as events that are potential crossing opportunities (in the form of yields and crossable gaps) and those that correspond to non-crossable gaps. Using this stratification, every cell in Exhibit 33 can be categorized as to whether the pedestrian correctly interpreted an event (for example utilized a crossable gap in both lanes) or not. Applying this framework to every cell, a total of five event outcome categories emerge:

1. **Correctly Accepted Crossing Opportunity:** Pedestrian “GO” in a crossable/safe situation.
2. **Falsely Rejected Crossing Opportunity:** Pedestrian “NoGO” in a crossable/safe situation.
3. **Correctly Rejected Non-Crossable Event:** Pedestrian “NoGO” in a non-crossable/unsafe situation.
4. **Falsely Accepted Non-Crossable Event:** Pedestrian “GO” in a non-crossable/unsafe situation.
5. **Inconclusive Event:** Pedestrian “GO” in a forced yield condition.

The first four categories correspond to a classical 2x2 event matrix that relates the real-world condition to the pedestrian response. The fifth category was introduced, since it is “inconclusive” whether a forced yield should be interpreted as an acceptable crossing strategy or not. Exhibit 34 summarizes the event classifications for the pre study at the RCW.

Exhibit 34 suggests that for the total of 686 events, 23.8% of crossings were correct utilizations of crossing opportunities and 58.6% of events were correctly rejected events. Only 6.0% were classified as missed opportunities and inefficient behavior, and 1.3% fell into the “unsafe” category. Also, 10.3% of events were associated with a forced yield and were labeled as inconclusive. Note that any O&M interventions were removed from the dataset prior to analysis (discussed separately) and so none of these forced yields resulted in a truly dangerous situation. However, in the absence of pedestrian and/or driver action, a forced yield can result in a collision.

Posttest Pedestrian Behavior at the RCW

The installation of the raised crosswalk was expected to assist pedestrians by encouraging more drivers to yield and by generally slowing down the conflicting traffic in the vicinity of the crosswalk. Since the treatment does not involve any form of signalization, the same near–far analysis framework was applied to the post dataset. Exhibit 35 plots the near- and far-lane events (same as pre analysis) for the RCW installation.

Exhibit 35 shows that the probability of encountering a yield after the RCW installation increased from 26.7% to 51.3% in the near lane. Further, the rate of yield utilization increased from 54.6% to 92.0%. The presence of the RCW may have led to a modified driver behavior that made it easier for pedestrians to detect the yield. In the near lane, 13.8% of yields were forced by pedestrians, which is slightly less than the 16.4% in the pre condition.

In the post data collection, pedestrians encountered 131 gaps, and 80 of those were crossable. The likelihood of encountering

Exhibit 34. Summary of pedestrian behavior, pre condition, RCW.

Pedestrian Decision	Crosswalk Condition		
	Crossable/Safe	Non-Cross./Unsafe	Inconclusive
GO	163 23.8%	9 1.3%	71 10.3%
NoGO	41 6.0%	402 58.6%	–

Exhibit 35. Near–far lane effects, post condition, for RCW.

		Far-Lane Event										
							Multiple Events					
Near-Lane Event	Lane Outcome	Rolling Yield	Stopped Yield	Forced Yield	X-Able Gap	Non-X. Gap	RY	STY	CG	FY	non-CG	Total
Rolling Yield	Utilized	4	5	6	6	0	2	1	2	1	0	**27**
	Non-Utlz.	2	0	0	0	3	0	0	0	0	0	**5**
Stopped Yield	Utilized	12	28	12	18	1	0	4	2	4	0	**81**
	Non-Utlz.	0	2	0	0	3	0	0	0	0	1	**6**
Forced Yield	Utilized	1	5	0	9	0	0	1	1	2	0	**19**
	Non-Utlz.	0	0	0	0	0	0	0	0	0	0	**0**
Crossable Gap	Utilized	5	11	13	35	1	1	0	7	2	0	**75**
	Non-Utlz.	0	0	0	0	3	0	0	0	0	2	**5**
Non-Cross. Gap	Utilized	0	1	0	1	3	0	0	0	0	0	**5**
	Non-Utlz.	0	1	0	4	37	0	0	0	0	4	**46**
Total		**24**	**53**	**31**	**73**	**51**	**3**	**6**	**12**	**9**	**7**	**269**

Exhibit 36. Availability and utilization statistics for post condition, RCW.

Post (n = 269)	Near Lane	Far Lane
Availability Statistics		
P(Y_Enc)	51.3%	46.8%
P(CG_Enc)	29.7%	31.6%
Utilization Statistics		
P(GO|Y)	92.0%	96.0%
P(GO|CG)	93.8%	95.3%

a crossable gap from all events was 29.7%, which is similar to the pre study (25.5%). However, the rate of crossable gap utilization increased from 78.9% to 93.8% in the near lane. Exhibit 36 shows the summary availability and utilization statistics.

Exhibit 36 shows that the availability of yield crossing opportunities about doubled with the installation of the raised crosswalk, while the availability of gap crossing opportunities remained largely unaffected. However, the rate of utilization of both types of opportunities increased drastically, with utilization rates well above 90%. Overall, far fewer events were (had to be) rejected by the pedestrian, as is evident in the summary statistics in Exhibit 37.

Exhibit 37 shows that for the total of 269 events, 53.2% of crossings were correct utilizations of crossing opportunities and 21.6% of events were correctly rejected events. Only 1.5% were classified as missed opportunities and inefficient behavior, and 2.6% fell into the "unsafe" category. Also, 21.2% of events were associated with a forced yield and were labeled as inconclusive.

A comparison of Exhibits 34 and 37 makes evident that the biggest difference between the pre and post data is a drastic reduction of rejected opportunities (reduced from 443 to 62 events). With the introduction of the raised crosswalk, drivers tended to yield more frequently, and many of these yields resulted in crossings. Furthermore, pedestrians seemed more comfortable accepting gaps, resulting in an overall drop of inefficient decisions from 6.0% to 1.5%. As a result of this more assertive behavior, the rate of potentially risky events about doubled, as did the rate of inconclusive events. Note that any O&M interventions were removed from the dataset prior to analysis (discussed separately) and so none of these forced yields resulted in a truly dangerous situation.

Performance Statistics for RCW

The installation of the RCW is expected to also affect the bottom-line delay and risk performance statistics for the pedestrians. Delay statistics in Exhibit 38 are provided for pedestrian delay in seconds, defined as the time difference between when the trial started and when the pedestrian initiated the crossing. The exhibit further shows the delay beyond the first oppor-

Exhibit 37. Summary of pedestrian behavior, post condition, RCW.

Pedestrian Decision	Crosswalk Condition		
	Crossable/Safe	Non-Cross./Unsafe	Inconclusive
GO	143 53.2%	7 2.6%	57 21.2%
NoGO	4 1.5%	58 21.6%	–

Exhibit 38. Average pedestrian delay statistics for RCW.

a) Observed Delay per Leg (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	15.6	1.5	57.1	15.9
Exit (n = 18)	18.4	3.0	84.9	19.4
Overall (n = 36)	17.0	1.5	84.9	17.6
Post				
Entry (n = 13)	6.7	3.6	12.2	2.7
Exit (n = 13)	9.4	4.0	18.2	3.7
Overall (n = 26)	8.0	3.6	18.2	3.5

b) Delay>Min (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	3.1	0.0	11.1	3.6
Exit (n = 18)	3.8	0.2	11.2	2.8
Overall (n = 36)	3.4	0.0	11.2	3.2
Post				
Entry (n = 13)	1.7	0.1	4.3	1.3
Exit (n = 13)	2.8	0.2	5.8	1.7
Overall (n = 26)	2.3	0.1	5.8	1.5

tunity (Delay>Min), which was defined as the time difference between the first yield or crossable gap encountered by the pedestrian and the actual crossing initiation. Statistics for all measures are for crossing one leg (two lanes) of the roundabout. The statistics shown are calculated from the average crossing performance for each subject. The total sample size was 18 and 13 subjects in the pre and post studies, respectively. Each data point represents the average of 16 approach crossings, half at the entry and half at the exit of the roundabout.

Exhibit 38 shows that the average pedestrian delay per leg decreased significantly between the pre and post conditions, from 17.0 s to 6.7 s (p = 0.0434). There was no significant difference between the delay experienced at the entry and exit portions of the crossing in the pre study. In the post study, the delay difference of 2.7 s higher average delay at the exit is significant at p = 0.0440. In addition to the average delay for all participants, it is important to emphasize that some participants experienced much larger delays. The highest average delay was 84.9 s in the pre study, and the single highest delay experienced by a study participant was 115.8 s (not shown). These figures do not include trials that were beyond the 2-min time-out limit. The maximum average delay in the post was only 11.2 s, and the single highest delay in the post condition was 57.4 s. Overall, the 2-min time-out limit was reached 9 times for all subjects in the pre condition and never after installation of the raised crosswalk. With installation of the RCW, the observed range and standard deviation of average delay were reduced, suggesting more consistent behavior across subjects.

The results for Delay>Min also show a reduction between the pre and post conditions from 3.4 to 2.3 s, but this difference was not statistically significant (p = 0.2117). Overall, the Delay>Min results suggest that the blind pedestrians did not miss a lot of crossing opportunities, but rather were delayed due their infrequent occurrence. Despite these low averages, some pedestrians experienced Delay>Min up to 48.4 s in the pre condition and up to 36.9 s the post case (not shown). The maximum average Delay>Min were 11.2 and 5.8 s, respectively.

Exhibit 39 shows the cumulative distribution of pedestrian delay at the PHB. The 85th percentile delay is highlighted.

The exhibit clearly shows a shift of the delay distribution, with pedestrians in the post condition overall experiencing lower delays. The 85th percentile delay across all participants was reduced from 31.0 to 13.4 s. The difference is also evident when looking at the crossing performance of individual

Exhibit 39. Cumulative delay distribution of pedestrian delay at RCW.

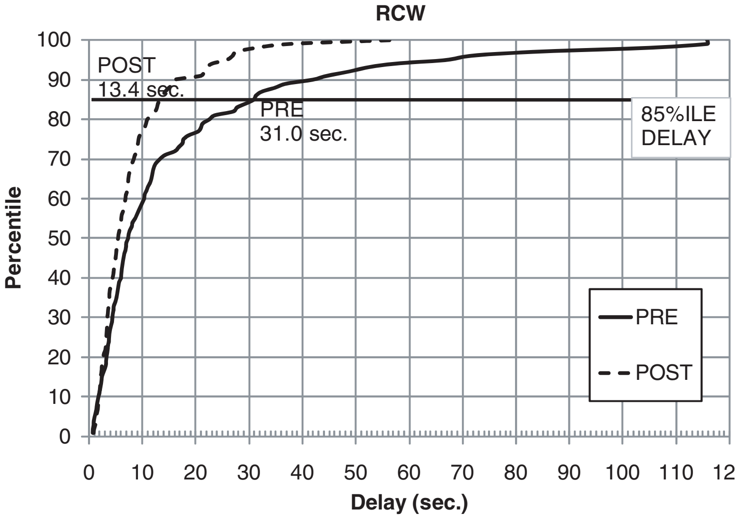


Exhibit 40. 85th percentile delay by subject – RCW.

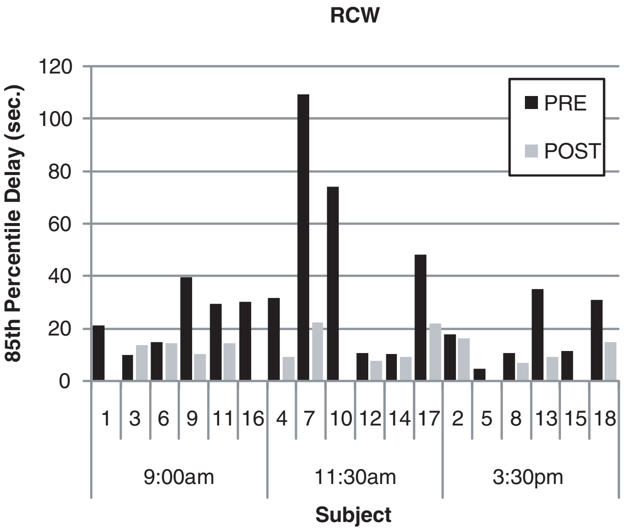


Exhibit 41. Latency and yield lost time statistics for north crosswalk.

a) Latency (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	6.5	1.3	15.3	4.0
Exit (n = 18)	8.1	1.9	41.4	8.7
Overall (n = 36)	7.3	1.3	41.4	6.7
Post				
Entry (n = 13)	4.5	2.3	6.8	1.5
Exit (n = 13)	6.1	2.2	11.2	2.8
Overall (n = 26)	5.4	2.2	11.2	2.4

b) Yield Lost Time (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	3.5	–0.8	9.0	2.5
Exit (n = 18)	0.8	–4.3	8.9	3.3
Overall (n = 36)	2.2	–4.3	9.0	3.2
Post				
Entry (n = 13)	3.4	1.2	6.2	1.3
Exit (n = 13)	2.4	0.5	3.6	0.9
Overall (n = 26)	2.9	0.5	6.2	1.2

participants. Exhibit 40 shows the 85th percentile delay for all participants in the pre and post condition. Note that participants 1, 5, 10, 15, and 16 did not participate in the post study.

The figure shows that the 85th percentile delay was reduced for every participant in the post condition but also that the effect was greatest for those that experienced high delay in the pre. So, in addition to reducing the overall delay, the RCW also created a more uniform distribution of delay, even for participants with presumably worse travel skills. Exhibit 40 further explores the relationship between 85th percentile delay and the time of day of the participation. From a visual analysis, no trends are observed.

The analysis further investigated two parameters intended to describe the efficiency with which a crossing opportunity is utilized. For utilized gaps, the *latency* is defined as the time between when the last vehicle went through the crosswalk and the time the pedestrian initiated the crossing. For utilized yields, the *yield lost time* is defined as the time between when a driver first slows down for a yield and the time the crossing is initiated. Note that in some cases, pedestrians may prefer to cross only after a car has come to a full stop (stopped yield) and so some inherent yield utilization time is expected. Exhibit 41 shows statistics for both measures.

The latency results in Exhibit 41 suggest that on average pedestrians wait 7.3 s into a crossable gap before initiating the crossing, suggesting inefficiency in decision-making. With the installation of the RCW, the average latency decreases slightly to 5.4 s ($p = 0.2767$).

For the YLT measure, pedestrians in the pre condition lose an average of 2.2 s before crossing in front of a yielding vehicle. However, the average maximum YLT was 9.0 s. In many cases, drivers will not be willing to wait this long, and a high YLT will therefore translate to an increased percentage of missed yields [lower $P(GO|Y)$]. Note that the minimum YLT is negative, suggesting that some pedestrians forced vehicles to yield (the yield was "utilized" before it occurred). The installation of the RCW had no significant effect on yield lost time.

The above measures primarily focus on the efficiency of crossing, and largely ignore the risk experienced by pedestrians. While delay and other efficiency measures are used frequently by engineers, they fail to capture the human element of crossing risk. The selected surrogate risk measure for this study is the number of times the O&M specialist had to intervene in the crossing. Exhibit 42 shows the frequency and rate of O&M interventions for all trials.

Exhibit 42 shows a drastic reduction in the occurrence of interventions. The percentage of trials that resulted in an O&M intervention is reduced from 2.8% to zero in the post condition. Following discussion in Ashmead et al. (2005), a 2.8% likelihood of a risky decision will result in a cumulative risk of 67.9% after 40 crossings (for example two crossings a day over 4 weeks with 5 working days per week). In the pre case, the exit lane had a slightly higher intervention rate than the entry, which is consistent with findings at other multi-lane roundabouts. However, given that interventions are very rare events, it is unlikely that the post intervention is an absolute zero, but rather small-enough to where it was not measurable at the given sample size. Exhibit 43 explores the distribution of O&M intervention across subjects and by time of day. Subjects that didn't participate in the post experiment are shown with a negative intervention rate to distinguish them from those with zero interventions that did participate.

Exhibit 42. O&M interventions for RCW.

O&M Interventions – RCW Crosswalk

Pre		Frequency	# of Crossings	Percent
	Entry	3	144	2.1%
	Exit	5	144	3.5%
	Overall	8	288	2.8%
Post				
	Entry	0	104	0.0%
	Exit	0	104	0.0%
	Overall	0	208	0.0%

Exhibit 43. O&M intervention rate by subject and time of day.

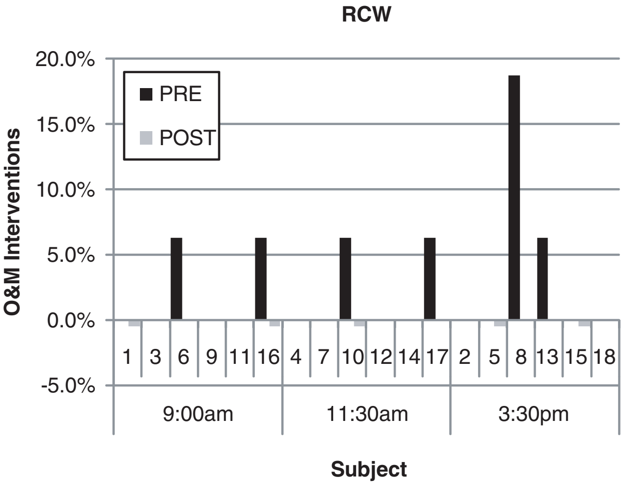


Exhibit 44. Summary of crossing performance pre and post RCW installation.

Performance Measure	Pre	Post
Yield Availability*	25.2%	49.1%
Gap Availability*	23.7%	30.7%
Yield Utilization*	61.7%	94.0%
Gap Utilization*	81.1%	94.5%
85th percentile Delay (s)	31.0	13.4
O&M Interventions	2.8%	0.0%

*Average of Near and Far Lane

RCW Summary

In summary, the installation of the raised crosswalk signal resulted in a large reduction of both delay and interventions for all study participants. The relative difference between pre and post studies was greatest for participants that experienced high delays in the pre condition, as the RCW created a more uniform distribution of delay across participants. The RCW further reduced the overall number of events, with much fewer rejected events. As more drivers yield, the relative frequency of gaps encountered decreases.

The installation of the RCW further seemed to enhance the efficiency with which crossing opportunities were utilized. The higher utilization rates can potentially be explained by the hypothesis that pedestrians felt more confident with the RCW in place and its effect on drivers. Alternatively, the RCW may have altered driver behavior in a way that made it easier to detect crossing opportunities (e.g., yielding more abruptly and closer to the crosswalk). A learning effect by pedestrians is unlikely because the single-lane roundabout comparison site did not show improvement in behavior. Exhibit 44 presents a summary of the pre and post crossing performance at the raised crosswalk.

In summary, the RCW seemed to have an impact on the availability of crossing opportunities in the form of yields and further increased the rate of opportunity utilization for both yields and gaps. The treatment therefore affects both driver behavior (yield availability) and pedestrian behavior (utilization). The effect on the behavioral parameters was large enough to significantly impact the bottom line in the form of greatly reduced delay and the reduction of O&M interventions to zero. While some pedestrians still encountered some high delay time in the post treatment installation, the overall effect was a reduction in the delay estimate itself as well as in the range and variability of the estimate. The biggest impact was notable for pedestrians who had high delays in the pre condition and whose post-treatment performance was within the range of that of more comfortable and experienced travelers.

PART 5

Detailed Two-Lane Roundabout: Golden, CO – PHB

Introduction

This section describes analysis results of data collected at the northern crosswalk of the two-lane roundabout in Golden at the intersection of Golden Road and Johnson Road (Exhibit 45). The analysis focus will be on pedestrian-related measures, including the availability and utilization of yield and gaps as well as pedestrian delay and O&M interventions. The measures are defined in the methodology chapter of this report.

Because of the two-lane approaches at this site, the document distinguishes between near-lane and far-lane effects at the crosswalk. These describe the vehicle state in the near and far lane relative to the position of the waiting pedestrian.

This section focuses on the north crosswalk with the treatment effect of the PHB (also known as a HAWK signal). The analysis presents findings in the pre and post conditions for the studied crosswalk sequentially.

The pre study was completed in July 2008, and a total of 18 blind travelers participated in the pre study. The treatment was installed following the pre study, and 13 of the original 18 participants returned for the post experiment in September 2008, allowing approximately 60 days for driver acclimation.

Pedestrian Hybrid Beacon Evaluation

Pedestrian Hybrid Beacon Treatment Overview

A PHB was installed at the northern crosswalk at the two-lane roundabout, as shown in Exhibit 46. The treatment was installed at the existing crosswalk location and was outfitted with an APS device to provide additional assistance to blind study participants.

The PHB is different from a conventional signal in that it remains dark for traffic unless a pedestrian presses the call button. When the pedestrian presses the button, the approaching drivers are given a "Flashing Yellow" indication requiring them to reduce speed and be prepared to stop for a pedestrian in the crosswalk.

The "Flashing Yellow" is followed by a "Solid Yellow" providing additional emphasis on the need to reduce speed and be prepared to stop. "Solid Yellow" then changes to "Solid Red." The law requires that drivers come to a complete stop when seeing a "Solid Red" signal indication. When approaching drivers see the "Solid Red," sighted pedestrians see the customary "Walk" signal and may begin to cross. Visually impaired pedestrians hear a speech message saying, "Walk Signal On." After a few seconds, the vehicle display will switch to a "Flashing Red" indication for the driver, as two red lights wig-wag back and forth. At this time drivers can proceed if the crosswalk to their immediate front is not occupied by any pedestrians. There may still be pedestrians completing their crossing when drivers see the signal turn from "Solid Red" to "Flashing Red." If a pedestrian is still in the lane, a driver must remain stopped until the path is clear. Per proposed language in the MUTCD, a driver approaching the signal during "Flashing Red" must first come to a stop before proceeding through the crosswalk. The PHB is timed to allow pedestrians to cross one side of the street (two lanes) at a time (entry or exit). Once they reach the splitter island, pedestrians will place a second signal call to complete the crossing to the far-side curb. The phasing sequence is outlined in Exhibit 47.

The PHB arrangement is intended to aid pedestrians who desire assistance in crossing from or to the median that separates the two directions of traffic, especially when traffic is heavy. It provides visually impaired pedestrians audible information through an APS device about when the "Walk" signal is on.

Pretest Pedestrian Behavior at the PHB Crosswalk

The NCHRP Project 3-78A analysis of single-lane crossings used a performance evaluation framework that described the availability of crossing opportunities, the rate of utilization of these opportunities, and the delay and risk associated with the crossings. For a single lane, the yield and gap events

Exhibit 45. Aerial view of roundabout.

Photo by Google

are uniquely defined by the vehicle state in the conflict lane. However, at a two-lane crossing the analysis needs to consider the vehicle state in both lanes. The following approach distinguishes between driver behavior in the near lane (the lane closest relative to the position of the pedestrian) and the far lane. Depending on the crossing location (entry/exit and curb/island), the near lane can be the inside or outside lane of the two-lane approach. The analysis defines the vehicle state in the near lane in five event categories:

1. **Rolling Yield (RY):** Pedestrian encounters a driver who has slowed down for the pedestrian, but has not come to a full stop.
2. **Stopped Yield (STY):** Pedestrian encounters a driver who has come to a stop, defined as moving at a speed less than 3 mph.
3. **Forced Yield (FY):** Pedestrian initiates crossing before the vehicle initiated the yield, but then forces the driver to slow down by entering the crosswalk.

Exhibit 46. Pedestrian hybrid beacon.

Photo by Lee Rodegerts

4. **Crossable Gap (CG):** Pedestrian encounters a gap large enough to safely cross the street without the need for a driver yield. A crossable gap is defined as the crossing width divided by 3.5 ft/s walking speed plus 2 s for start time and safety buffer.
5. **Non-Crossable Gap (non-CG):** Pedestrian encounters a gap between vehicles shorter than the crossable gap threshold.

The vehicle state in the far lane is defined relative to the near-lane condition in five principal categories: rolling yield, stopped yield, crossable gap, non-crossable gap, and multiple events. The last category indicates that more than one event took place in the far lane during one near-lane event. For example, several cars could have gone through the far lane during one large gap in the near lane. For multiple events, the last event in the sequence is considered for analysis. Exhibit 48 shows the near-lane and far-lane effects for the pre condition at the PHB crosswalk. The near lane event outcomes are classified as to whether they are utilized by the pedestrians.

Exhibit 48 shows that from a total of 603 events, participants encountered 194 yield events in the near lane (32.2%) and did not utilize 33 rolling yields and 39 stopped yields. The corresponding overall rate of yield utilization in the near lane is 62.9%. A subset of these near-lane yields (15.5%) were

Exhibit 47. Phasing sequence for PHB (source: MUTCD).

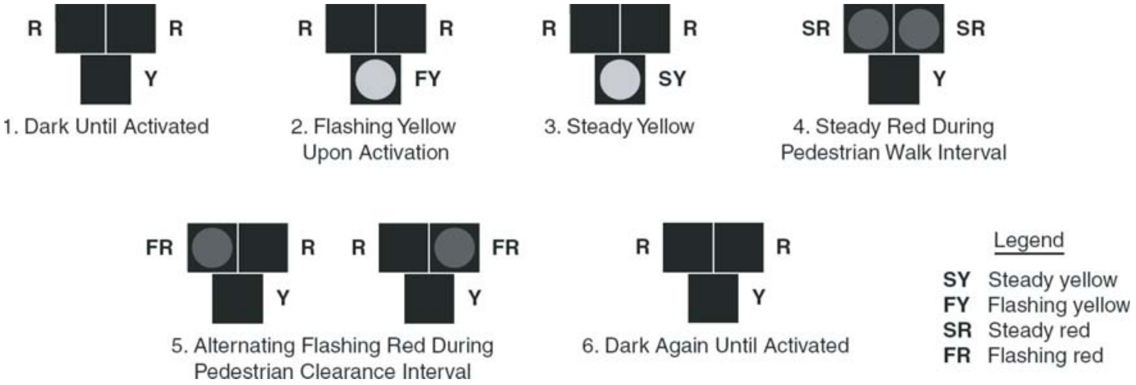


Exhibit 48. Near–far lane effects, pre condition, for PHB crosswalk.

		Far-Lane Event										
							Multiple Events					
Near-Lane Event	**Lane Outcome**	**Rolling Yield**	**Stopped Yield**	**Forced Yield**	**X-Able Gap**	**Non-X. Gap**	**RY**	**STY**	**CG**	**FY**	**non-CG**	**Total**
Rolling Yield	Utilized	1	4	3	6	1	0	1	1	1	0	**18**
	Non-Utlz.	3	4	0	1	24	1	0	0	0	0	**33**
Stopped Yield	Utilized	2	24	10	21	0	2	4	8	3	0	**74**
	Non-Utlz.	7	6	0	1	19	1	0	0	0	5	**39**
Forced Yield	Utilized	2	4	8	11	0	1	0	3	1	0	**30**
	Non-Utlz.	0	0	0	0	0	0	0	0	0	0	**0**
Crossable Gap	Utilized	8	7	22	82	0	2	2	19	9	0	**151**
	Non-Utlz.	0	1	0	1	17	0	0	1	0	2	**22**
Non-Cross. Gap	Utilized	0	1	1	2	0	0	0	1	0	0	**5**
	Non-Utlz.	6	10	0	13	185	2	0	2	0	13	**231**
Total		**29**	**61**	**44**	**138**	**246**	**9**	**7**	**35**	**14**	**20**	**603**

yields forced by the pedestrian. The analysis of the far-lane event shows that a majority of the non-utilized yields were attributable to either non-crossable gaps or multiple events in the far lane. Overall, only 22 events with yields in both lanes were non-utilized, including yields in the multiple events category, which indicates very good overall judgment of the perceived risk.

Similarly, of the 22 non-utilized crossable gaps, 19 had non-crossable gaps in the far lane. In total, pedestrians encountered 28.7% crossable gaps in both the near and far lanes. In the near lane, 87.3% of crossable gaps were utilized, along with 89.0% in the far lane. The crossing opportunity availability and utilization statistics are summarized in Exhibit 49.

The results in Exhibit 49 can be interpreted as events that are potential crossing opportunities (in the form of yields and crossable gaps) and as those that correspond to non-crossable gaps. Using this stratification, every cell in Exhibit 49 can be categorized as to whether the pedestrian correctly interpreted an event (for example, utilized a crossable gap in both lanes) or not. Applying this framework to every cell, a total of five event outcome categories emerge:

1. **Correctly Accepted Crossing Opportunity:** Pedestrian “GO” in a crossable/safe situation.
2. **Falsely Rejected Crossing Opportunity:** Pedestrian “NoGO” in a crossable/safe situation.
3. **Correctly Rejected Non-Crossable Event:** Pedestrian “NoGO” in a non-crossable/unsafe situation.
4. **Falsely Accepted Non-Crossable Event:** Pedestrian “GO” in a non-crossable/unsafe situation.
5. **Inconclusive Event:** Pedestrian “GO” in a forced yield condition.

Exhibit 49. Summary of availability and utilization statistics, PHB crosswalk, pre.

Pre (n = 603)	Near Lane	Far Lane
Availability Statistics		
P(Y_Enc)	32.2%	27.2%
P(CG_Enc)	28.7%	28.7%
Utilization Statistics		
P(GO|Y)	62.9%	75.0%
P(GO|CG)	87.3%	89.0%

The first four categories correspond to a classical 2x2 event matrix that relates the real-world condition to the pedestrian response. The last category applies to events associated with forced yields. A forced yield may involve some risk if neither driver or pedestrian acts to avoid a collision. However, many participants appeared to be deliberately forcing yields, which makes it difficult to discern the level of true risk from the data. Exhibit 50 summarizes the event classification for the pre study at the RCW crosswalk.

Exhibit 50 suggests that overall, 32.2% of crossings are classified as correct utilizations of crossing opportunities and 49.4% of events were correctly rejected events. Only 4.5% were classified as missed opportunities and inefficient behavior, and 1.0% fell into the potentially risky category (after O&M interventions were removed from the data). In addition, 12.9% fell into the inconclusive category and were associated with a forced yield in either the near or far lane.

Posttest Blind Pedestrian Behavior at the PHB Crosswalk

With the installation of the PHB, the analysis framework has to be modified from the pre condition. Pedestrians now encounter a signal indicating that the signal phase is either W, FDW, or DW. Blind pedestrians hear a locator tone during the DW and FDW phases and a speech message during the W phase. The appropriate crossing behavior is therefore

Exhibit 50. Summary of pedestrian behavior, pre condition, PHB crosswalk.

Pedestrian Decision	Crosswalk Condition Crossable/Safe	 Non-Cross./Unsafe	 Inconclusive
GO	194 32.2%	6 1.0%	78 12.9%
NoGO	27 4.5%	298 49.4%	–

linked to the signal indication, and the analysis of the concurrent vehicle states becomes a secondary item of interest. Exhibit 51 shows the frequency of crossing initiation for the (blind) pedestrian relative to PHB signal phases.

The results show that only 36.7% of pedestrians crossed in the intended "Walk" phase and that most (39.0%) actually initiated the crossing just before the "Walk" phase (and the APS alert) in the vehicular solid yellow. In other words, they began to cross following their pressing the call button but prior to the APS message. Further, 11% crossed even earlier, in the vehicle "Flashing Yellow" phase, and 13.3% didn't cross until the "Flashing Don't Walk" phase. Overall, only three times (out of 208 lane crossings) did pedestrians not cross in the first crossing phase and have to reactivate the signal.

These figures suggest that the study participants rely heavily on their own personal judgment, even with the signal beacon in place. Pedestrians tended not to cross in "Walk" if they were unsure about whether vehicles had in fact stopped. Even when the APS confirmed to the blind pedestrian that a "Red" signal indication was being presented to an approaching driver, some would still not cross until they were confident that it was safe to do so. Similarly, they would readily cross before the "Walk" phase if they perceived a crossing opportunity. To illustrate this point, Exhibit 52 shows the near and far-lane event outcomes (same as pre analysis) by signal phase.

The results show that almost all of the early crossing events that started in "Flashing" or "Solid Yellow" phases were associated with crossing opportunities. The majority of these were yields in both lanes (68 out of 105 events, or 64.7%), although 52.9% of those were associated with a forced yield in at least one of the lanes. The rest were some combination of yields and crossable gap, with only one exception, where a non-crossable gap existed in the far lane. No rejected opportunities were observed in the two early phases, suggesting great efficiency for those pedestrians who chose to cross there. However, 57.1% of the crossings were associated with a forced yield, which may indicate some level of risk depending on pedestrian and driver awareness of the situation.

Events in the "Walk" phase include a significant number of rejected events (28.0%), mostly in the form of non-crossable gaps. This suggests that a portion of drivers did not comply with the signal indication, a pattern that is explored in more detail later. Some events (4.7%) suggest inefficient behavior (i.e., failure to cross during "Walk" phase), pointing to uncertainty in crossing for some pedestrians. The 32.7% "inconclusive" events were all associated with forced yields, indicating that the pedestrian initiated the crossing before the driver initiated the yield. Presumably, these events are acceptable at a signal; however, there is still some degree of risk if those drivers had been unaware of the pedestrian action.

Exhibit 51. Blind pedestrian crossings at PHB by signal phase (% of all crossings).

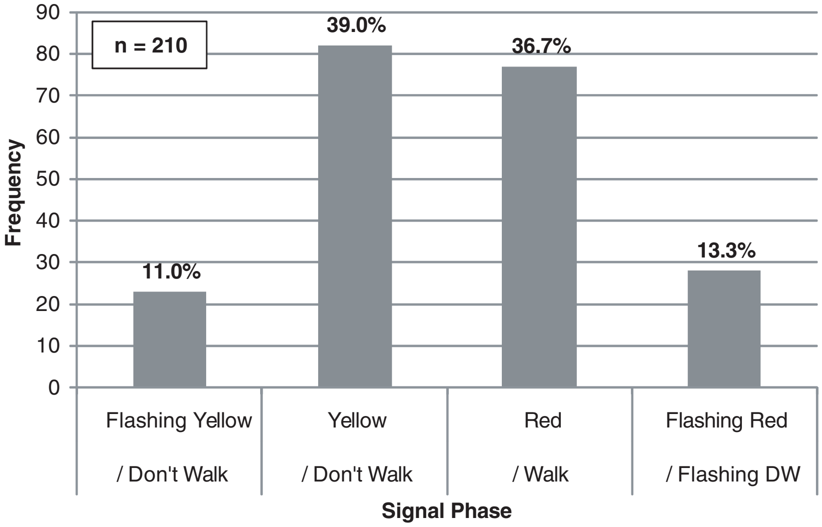


Exhibit 52. Near-far lane effects post condition for PHB crosswalk by signal phase.

		Phase = Flashing Yellow										
Near-Lane Event	**Near-Lane Outcome**	**Rolling Yield**	**Stopped Yield**	**Forced Yield**	**X-Able Gap**	**Non-X. Gap**	**Multiple Events**					**Total**
							RY	**STY**	**CG**	**FY**	**non-CG**	
Rolling Yield	Utilized	.	.	.	.	.	.	.	.	.	.	**0**
	Non-Utlz.	.	.	.		.	.	.	.	.	.	**0**
Stopped Yield	Utilized	1	2	2	0							**5**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Forced Yield	Utilized	1	5	4	0	.	.	.	.	.	.	**10**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Crossable Gap	Utilized	0	1	6	1	.	.	.	.	.	.	**8**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Non-Cross. Gap	Utilized	.	.	.	.	.	.	.	.	.	.	**0**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Total	**0**	**2**	**8**	**12**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**23**

		Phase = Yellow										
Near-Lane Event	**Near-Lane Outcome**	**Rolling Yield**	**Stopped Yield**	**Forced Yield**	**X-Able Gap**	**Non-X. Gap**	**Multiple Events**					**Total**
							RY	**STY**	**CG**	**FY**	**non-CG**	
Rolling Yield	Utilized	4	4	7	2	0	0	.	0	.	.	**17**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Stopped Yield	Utilized	1	14	4	2	1	0		0			**22**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Forced Yield	Utilized	6	5	8	5	0	0	.	0	.	.	**24**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Crossable Gap	Utilized	2	4	7	4	0	1	.	1	.	.	**19**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Non-Cross. Gap	Utilized	.	.	.	.	.	.	.	.	.	.	**0**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Total	**0**	**13**	**27**	**26**	**13**	**1**	**1**	**0**	**1**	**0**	**0**	**82**

		Phase = Walk/Red										
Near-Lane Event	**Near-Lane Outcome**	**Rolling Yield**	**Stopped Yield**	**Forced Yield**	**X-Able Gap**	**Non-X. Gap**	**Multiple Events**					**Total**
							RY	**STY**	**CG**	**FY**	**non-CG**	
Rolling Yield	Utilized	4	5	5	2	0	0	1	0	0	.	**17**
	Non-Utlz.	0	2	0	0	4	0	2	0	0	.	**8**
Stopped Yield	Utilized	4	10	2	3	0	0	1	0	0		**20**
	Non-Utlz.	0	1	0	0	1	0	0	0	0	.	**2**
Forced Yield	Utilized	4	3	5	4	0	1	1	1	2	.	**21**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Crossable Gap	Utilized	1	6	5	4	0	0	0	1	2	.	**19**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Non-Cross. Gap	Utilized	.	.	.	.	.	.	.	.	.	.	**0**
	Non-Utlz.	2	0	0	0	18	0	0	0	0	.	**20**
Total	**0**	**15**	**27**	**17**	**13**	**23**	**1**	**5**	**2**	**4**	**0**	**107**

		Phase = Flashing Don't Walk/Flashing Red										
Near-Lane Event	**Near-Lane Outcome**	**Rolling Yield**	**Stopped Yield**	**Forced Yield**	**X-Able Gap**	**Non-X. Gap**	**Multiple Events**					**Total**
							RY	**STY**	**CG**	**FY**	**non-CG**	
Rolling Yield	Utilized	0	3	0	0	.	1	0	1	1	.	**6**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Stopped Yield	Utilized	0	4	0	0		0	0	0	1		**5**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Forced Yield	Utilized	0	3	3	2	.	1	1	1	1	.	**12**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Crossable Gap	Utilized	1	0	1	1	.	0	0	1	1	.	**5**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Non-Cross. Gap	Utilized	.	.	.	.	.	.	.	.	.	.	**0**
	Non-Utlz.	.	.	.	.	.	.	.	.	.	.	**0**
Total	**0**	**1**	**10**	**4**	**3**	**0**	**2**	**1**	**3**	**4**	**0**	**28**

Exhibit 53. Summary of availability and utilization statistics, PHB crosswalk, post.

Post (n = 242)	Near Lane	Far Lane
Availability Statistics		
P(Y_Enc)	76.4%	68.6%
P(CG_Enc)	70.2%	19.8%
Utilization Statistics		
P(GO|Y)	92.4%	97.6%
P(GO|CG)	100.0%	100.0%

Those pedestrians who rejected opportunities in the "Walk" phase ultimately crossed in the "Flashing Don't Walk" phase. Again, the majority of events here are related to yield events with drivers stopped at the signal. No rejected opportunities or inefficient events were observed, but again many events fall into the inconclusive category. Exhibit 53 summarizes the availability and utilization statistics for the post treatment installation data. Since it appeared from the analysis above that most pedestrians crossed independently of the signal indication, the results are presented in light of the near–far lane framework discussed above. This also ensures that the numbers are directly comparable to the pre condition results.

The summary statistics suggest a large increase in the availability of both yields and gaps from the pre condition (Exhibit 49), as well as more efficient utilization of these crossing opportunities. Exhibit 54 shows a summary of all events for the post condition by signal phase.

Exhibit 54 shows that crossing performance in the early phases ("Flashing Yellow" and "Solid Yellow") was generally characterized by mostly correctly accepted crossing opportunities as well as a large portion of forced yields (inconclusive events). Virtually no risky or inefficient events were observed during these phases.

For the intended crossing phase (Red/Walk), 39.3% of crossings were classified as correct utilizations of crossing opportunities, and 23.4% of events were correctly rejected events. Further, 4.7% were classified as missed opportunities and inefficient behavior, and none were observed in the potentially risky category. Similar to the early phases, many events (32.7%) fell into the inconclusive category and were associated with a forced yield in either the near or far lane. Those pedestrians that waited to initiate crossing during the "Flashing Red" phase mostly made correct "GO" decisions, but more than half were once again associated with forced yields.

A notable difference between Exhibits 49 and 53 for pre and post data is a drastic reduction in the rejected opportunities. With the introduction of the signal, drivers tended to yield much more frequently, and many of these yields resulted in crossings. The proportion of inefficient decisions was reduced slightly, as was the rate of potentially risky events. The rate of inconclusive events saw a large increase. As discussed above, these events are associated with forced yields, where none resulted in an O&M intervention. It is unclear whether a forced yield at a signal can truly be classified as a risky event since drivers are presumably prepared to stop given that the signal has been activated. However, in combination with red-light running events, some risk may remain. The discussion below examines in more detail the risk and delay performance measures.

Performance Statistics at the PHB Crosswalk

The changed pedestrian and driver behavior that took place with the introduction of the PHB affects the delay and risk performance measures. Delay statistics in Exhibit 55 are provided for pedestrian delay in seconds, defined as the time difference between the time a trial started and when the pedestrian

Exhibit 54. Summary of pedestrian behavior post condition, PHB crosswalk.

Pedestrian Decision	Crosswalk Condition Crossable/Safe		Non-Cross./Unsafe		Inconclusive	
Phase = Flashing Yellow/Don't Walk (n = 23)						
GO	5	21.7%	0	0.0%	18	78.3%
NoGO	0	0.0%	0	0.0%	–	0.0%
Phase = Yellow/Don't Walk (n = 82)						
GO	39	47.6%	1	1 .2%	42	51.2%
NoGO	0	0.0%	0	0.0%	–	0.0%
Phase = Red/Walk (n = 107)						
GO	42	39.3%	0	0.0%	35	32.7%
NoGO	5	4.7%	25	23.4%	–	0.0%
Phase = Flashing Red/Flashing Don't Walk (n = 28)						
GO	12	42.9%	0	0.0%	16	57.1%
NoGO	0	0.0%	0	0.0%	–	0.0%

Exhibit 55. Average pedestrian delay statistics for PHB crosswalk.

a) Observed Delay per Leg (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	14.9	2.3	36.5	10.1
Exit (n = 18)	17.1	3.6	46.5	12.0
Overall (n = 36)	16.0	2.3	46.5	11.0
Post				
Entry (n = 13)	5.9	2.6	14.6	3.2
Exit (n = 13)	5.8	3.5	11.7	2.4
Overall (n = 26)	5.8	2.6	14.6	2.8

b) Delay>Min (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	4.5	0.2	11.9	3.5
Exit (n = 18)	3.9	0.0	11.8	3.9
Overall (n = 36)	4.2	0.2	11.9	3.7
Post				
Entry (n = 13)	1.4	0.2	3.1	1.0
Exit (n = 13)	1.4	0.2	3.0	0.9
Overall (n = 26)	1.4	0.2	3.0	0.9

initiated the crossing. The exhibit further shows the delay beyond the first opportunity (Delay>Min), which was defined as the time difference between the first yield or crossable gap encountered by the pedestrian and the actual crossing initiation. The crossable gap definition assumed crossing of two lanes at one leg of the roundabout. All statistics shown are calculated from the average performance of each individual subject. The sample sizes in the pre and post conditions are 18 and 13 participants, respectively.

Exhibit 55 shows that the average pedestrian delay per leg in the post condition decreased significantly from that in the pre condition, from 16.0 s to 4.2 s (p = 0.0007). There was no significant difference between the delay experienced at the entry and exit portions of the crossing in either study. In addition to reporting the average delay for all participants, it is important to emphasize that some individual participants experienced much larger delays. The highest average delay for a participant was 46.5 s in the pre and 14.6 s in the post case. However, the single highest delay experienced by a study participant was 100.2 s (not shown in the exhibit). The single highest delay in the post condition was 56.3 s, indicating that some pedestrians did not cross during the first "Walk" phase. The reported delay figures further do not include trials that were terminated when the subject's wait time exceeded the 2-min time-out limit. Overall, the 2-min time-out limit was reached in 3 of 288 lane crossings for all subjects in the pre condition and never with the PHB present (208 lane crossings).

The results for Delay>Min also show a significant reduction between the pre and post conditions from 4.5 s to 1.4 s (p = 0.0044). Overall, the Delay>Min results suggest that the blind pedestrians did not miss many crossing opportunities. Despite these low averages, some pedestrians experienced Delay>Min of up to 33.0 s in the pre condition and up to 11.4 s the post case (not shown). The highest average Delay>Min values were 11.9 s and 3.1 s, respectively.

Exhibit 56 shows the cumulative distribution of pedestrian delay at the PHB. The 85th percentile delay is highlighted.

The exhibit clearly shows a shift in the delay distribution, with pedestrians in the post condition experiencing much lower delays. The 85th percentile delay was reduced from 29.8 s to

Exhibit 56. Cumulative distribution of pedestrian delay at PHB crosswalk.

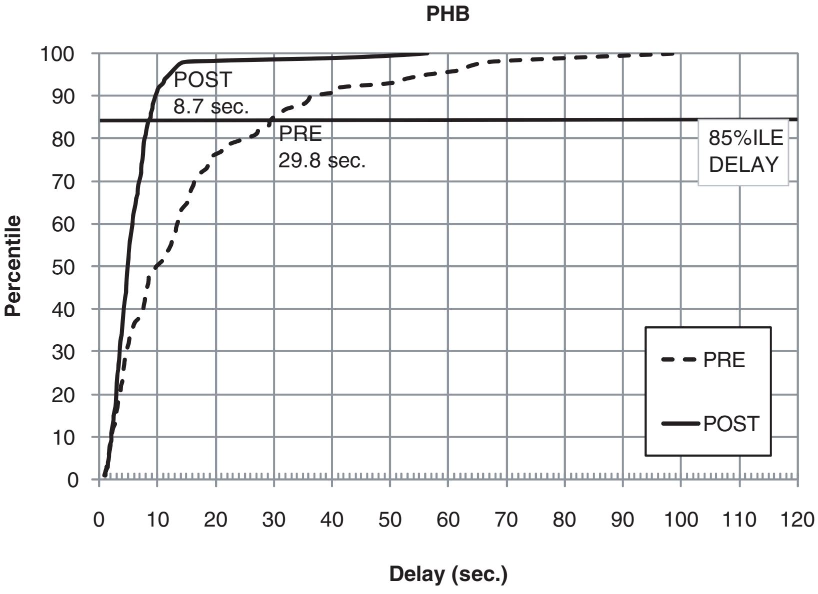
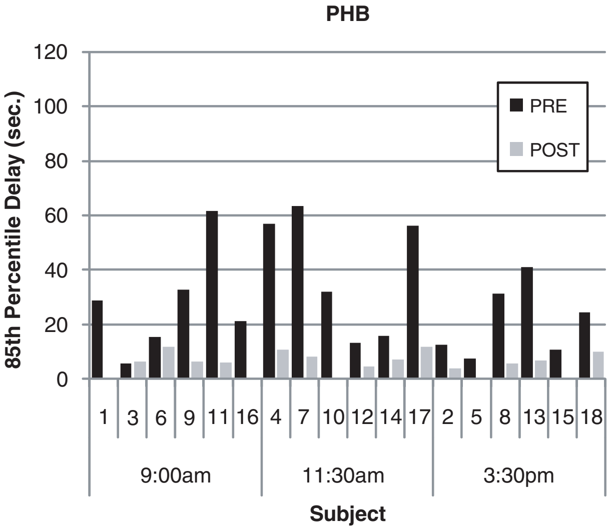


Exhibit 57. 85th percentile delay by subject – PHB crosswalk.



8.7 s. The difference is also evident when examining the crossing performance of individual participants. Exhibit 57 shows the 85th percentile delay for all participants in the pre and post condition. Note that subjects labeled 1, 5, 10, 15, and 16 did not participate in the post study.

Exhibit 57 shows that the 85th percentile delay was reduced for every participant in the posttest condition. Further, the effect appeared to be greatest for those subjects who experienced high delays in the pre study. So, in addition to reducing the overall delay, the PHB also created a more uniform distribution of delay, even for participants with presumably modest travel skills. The data in Exhibit 57 are arranged by the time of day the subjects participated in the study. A visual comparison does not show a significant effect on performance by time of day.

The team further investigated two parameters intended to describe the efficiency with which a crossing opportunity is utilized. For utilized gaps, the *latency* is defined as the time difference between a vehicle entering the crosswalk and the time the pedestrian initiated the crossing. For utilized yields, the *YLT* is defined as the time difference between the driver first slowing down for a yield and the time the crossing is initiated. Note that in some cases, pedestrians may prefer to cross only after a car has come to a full stop (stopped yield) and so some inherent yield utilization time is expected. Exhibit 58 shows statistics for both measures in the pre and post cases.

The latency results in Exhibit 58 suggest that on average pedestrians wait 5.9 s into a crossable gap before initiating the crossing, suggesting inefficiency in decision-making. With the installation of the PHB, the average latency decreases slightly to 4.8 s; however, that difference is not statistically significant (p = 0.2363). Both the range and standard deviation of the latency estimate are reduced in the post condition.

Exhibit 58. Latency and yield lost time statistics for PHB crosswalk.

a) Latency (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	5.0	1.4	10.1	2.9
Exit (n = 18)	7.0	3.0	14.9	3.5
Overall (n = 36)	5.9	1.4	14.9	3.3
Post				
Entry (n = 13)	4.4	2.3	7.9	1.8
Exit (n = 13)	5.2	2.9	8.2	1.7
Overall (n = 26)	4.8	2.3	8.2	1.7

b) Yield Lost Time (s)

Pre	Avg.	Min.	Max.	Std. Dev.
Entry (n = 18)	2.7	-1.7	9.9	3.2
Exit (n = 18)	1.2	-4.9	8.7	3.3
Overall (n = 36)	1.9	-4.9	9.9	3.3
Post				
Entry (n = 13)	-0.4	-3.2	3.3	1.9
Exit (n = 13)	-0.3	-5.1	2.7	2.4
Overall (n = 26)	-0.4	-5.1	3.3	2.1

For the YLT measure, pedestrians in the pre condition waited an average of 2.7 s before crossing in front of an already yielding vehicle. However, the maximum average YLT was 9.9 s, and individual YLT observations were even higher. In many cases, drivers may not be willing to wait this long and a high YLT will therefore translate to an increased percentage of missed yields [lower P(GO|Y)] or even an unsafe condition where both driver and pedestrian proceed simultaneously. Note that the YLT can be negative, suggesting that some pedestrians forced vehicles to yield. After installation of the PHB, many pedestrians crossed with the signal and thus before the vehicles had yielded, resulting in an average YLT of –0.4 s. The maximum average YLT also decreased to 3.3 s, suggesting a quicker response to the yielding vehicle.

The above measures primarily focus on the efficiency of crossing and largely ignore the explicit risk experienced by pedestrians. While delay and other efficiency measures are used frequently by engineers, they fail to capture the human element of crossing risk. The selected surrogate risk measure for this study is the number of times the O&M specialist had to intervene in the crossing. Exhibit 59 shows the frequency and rate of O&M interventions for all trials.

Exhibit 59 shows a drastic reduction in the occurrence of interventions. The percentage of trials that resulted in an O&M intervention is reduced from 2.4% to zero in the post condition. In the pre case, the entry lane actually had a higher intervention rate than the exit, which is contrary to findings at other multi-lane roundabouts (Guth et al. 2005). Following discussion in Ashmead et al. (2005), a 2.4% likelihood of a risky decision will result in a cumulative risk of 62.2% after

Exhibit 59. O&M interventions for PHB crosswalk.

O&M Interventions – PHB Crosswalk

Pre		Frequency	# of Crossings	Percent
	Entry	5	144	3.5%
	Exit	2	144	1.4%
	Overall	7	288	2.4%
Post				
	Entry	0	104	0.0%
	Exit	0	104	0.0%
	Overall	0	208	0.0%

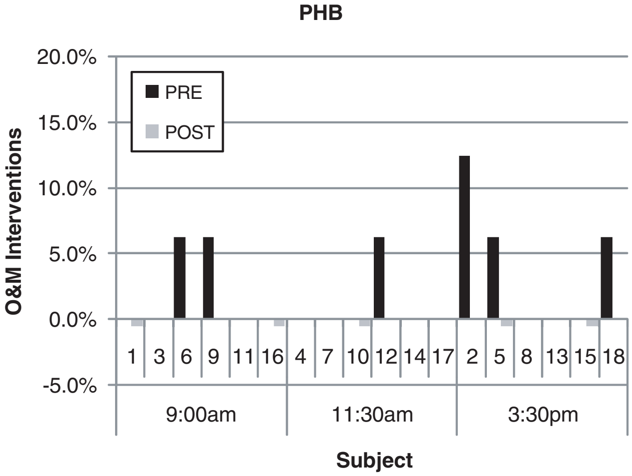
40 crossings (for example two crossings a day over 4 weeks with 5 working days per week). However, given that interventions are very rare events, it is unlikely that the post intervention is an absolute zero, but rather is small enough to where it was not measurable at the given sample size.

Exhibit 60 explores the distribution of interventions by subject and by time of day. Subjects who didn't return for the post experiment are shown with negative intervention rates to distinguish them from participants with zero interventions. The intervention rates show no trend by time of day. The figure makes evident that several participants didn't experience any interventions even in the before case at the given sample size of 16 lane crossings. Given the rare nature of the intervention measure, a zero rate should not be interpreted as a perfectly safe crossing.

Driver Behavior at the PHB

In the evaluation of the PHB, an important question of interest to traffic engineers is the effect of the signal on vehicle traffic flow. The driver behavior analysis described herein has two main components. First, the behavior of drivers relative to the signal phases is intended to capture driver understanding of and compliance with the signal indication. Second, the impact of the PHB installation on pedestrian-induced vehicle queues at the crosswalk is examined.

Exhibit 60. O&M interventions by subject and by time of day.



Driver understanding of and compliance with the PHB can be evaluated by relating the driver stopping behavior to the indicated signal phase. Exhibit 61 shows a summary of 426 vehicle events that were observed during and just after the trial as a function of PHB signal phase. The exhibit shows the number of drivers who yielded (rolling or stopped yield) in each of five signal phases: "Blank," "Flashing Yellow," "Solid Yellow," "Solid Red," and "Flashing Red." It then relates all vehicle events to the phase that was active when the vehicle crossed the plane of the crosswalk. The exhibit further contains a record of all vehicles that did not yield.

The results in Exhibit 61 show that many drivers who encountered a pedestrian at a crosswalk yielded even before the signal was activated, while others didn't stop at all, even when the signal was in the solid red phase. The events include all drivers who in some way interacted with the PHB signal or the pedestrian. The exhibit does not include any events that occurred before the signal was activated or after the trial was completed. Exhibit 62 plots two categories of driver behavior for each signal phase: (1) vehicles stopped or stopping, and (2) vehicles proceeding through the crosswalk.

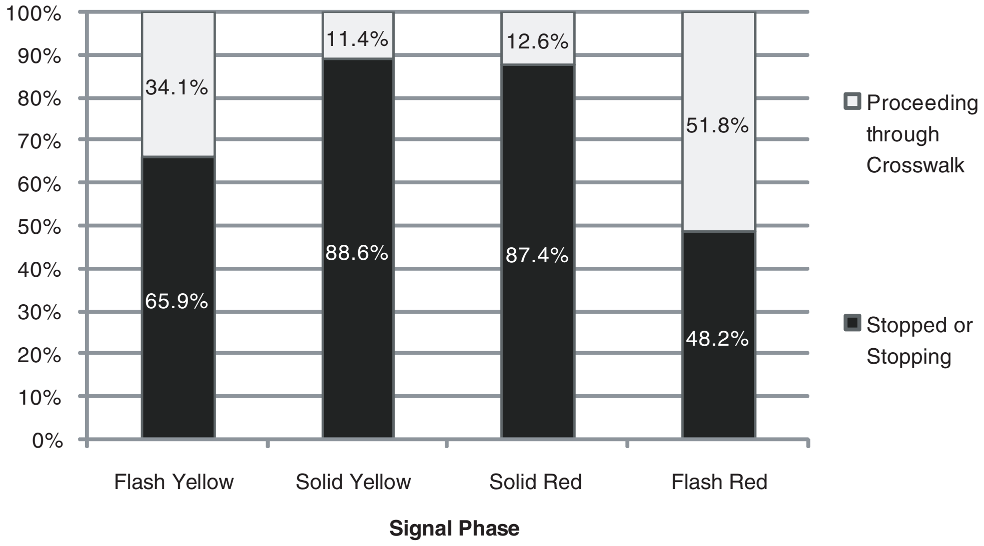
The exhibit shows that 34.1% proceeded through the crosswalk in "Flashing Yellow," which is permitted behavior. As the signal changes to solid yellow, still 11.4% of drivers proceed through the crosswalk, which is allowable if the vehicles were too close to the crosswalk to come to a stop. However, even during the "Solid Red," 12.6% of observed vehicles proceeded through the crosswalk. This figure is a concern, since drivers are legally required to stop for the red signal indication and because pedestrians expected a crossing opportunity. Driver behavior during "Flashing Red" shows that almost half of the drivers (48.2%) remained stopped, suggesting some inefficiency in driver behavior in response to the PHB.

The second part of the analysis focuses on the impact of the PHB installation on vehicle queues. Exhibit 63 shows the statistics for the maximum vehicle queue lengths in the pre and

Exhibit 61. Vehicle events by yielding and stopping phases at PHB.

		Yielding Vehicles and Phase Yielding Is Initiated						Non-Yielding Vehicles
	Signal Phase	**Blank**	**Flash Y**	**Solid Y**	**Solid R**	**Flash R**	**TOTAL**	
Crossing Phase	Flash Yellow	3	2	–	–	–	**5**	39
	Solid Yellow	3	2	0	–	–	**5**	15
	Solid Red	6	3	4	0	–	**13**	15
	Flash Red	20	20	31	15	15	**101**	72
	Blank	13	18	41	36	53	**161**	n/a
	TOTAL	45	45	76	51	68	**285**	**141**
							Total Vehicle Events	**426**

Exhibit 62. Evaluation of driver behavior at PHB.



post conditions. The maximum queue length was defined as the longest pedestrian-induced queue length that was observed during or just after a pedestrian crossing. Queues were measured relative to the crosswalk and therefore do not include additional vehicles that were waiting to enter the roundabout downstream of the crosswalk (at the entry). Vehicle queues are combined for both lanes since no significant difference was observed between queues in the inside and outside lanes. Vehicle queue statistics are shown separately for entry and exit lanes.

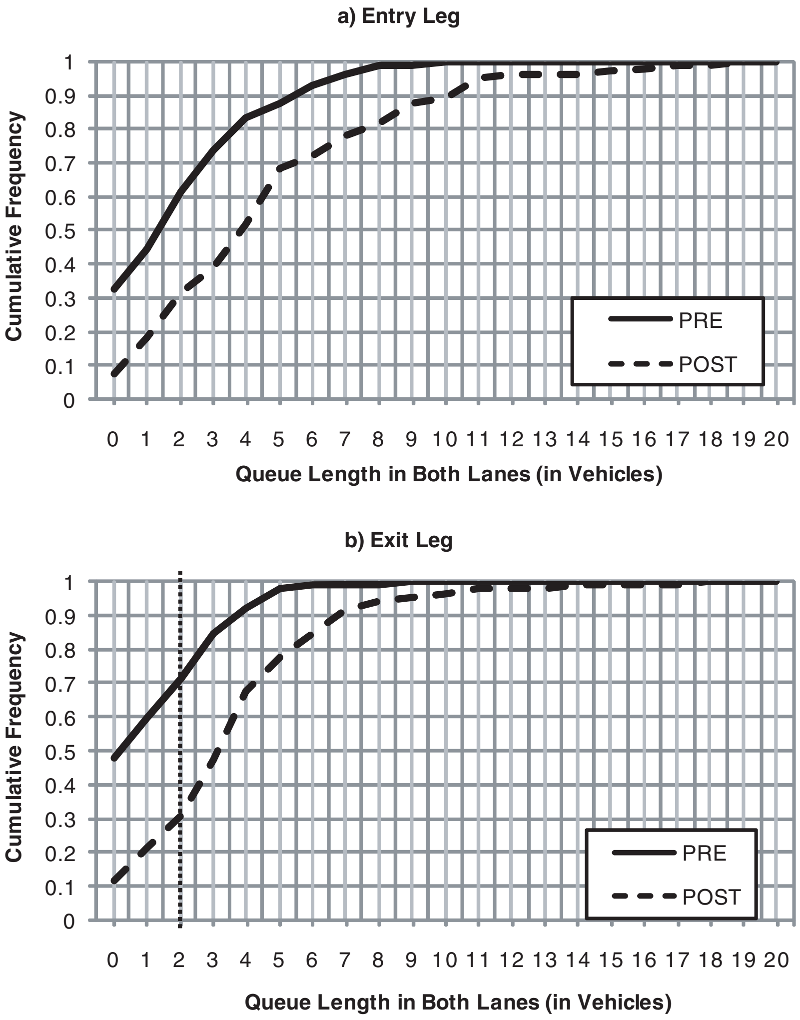
Exhibit 63. Maximum queue length statistics for PHB installation.

Maximum Vehicle Queues for Both Lanes (in Vehicles)					
Pre		**Avg.**	**Min.**	**Max.**	**Std. Dev.**
	Entry (n = 104)	2.3	0.0	10.0	2.4
	Exit (n = 104)	1.5	0.0	9.0	1.8
	Total (n = 208)	1.9	0.0	10.0	2.1
Post					
	Entry (n = 104)	5.0	0.0	19.0	3.9
	Exit (n = 104)	3.9	0.0	18.0	3.0
	Total (n = 208)	4.4	0.0	19.0	3.5

Exhibit 63 shows that the average maximum queue length increased from 2.3 to 5.0 vehicles at the entry and from 1.5 to 3.9 vehicles at the exit over both approach lanes. The increases in average maximum queues are significant at $p < 0.0001$. With available queue storage of two vehicles (one per lane) at the exit leg, it is evident that the maximum queue sometimes spilled back into the circulating lane, although the average queue is expected to be less than the reported max queue. The queue spillback effect is also evident in Exhibit 64, which shows the cumulative distributions of maximum queue lengths. The dashed line in Exhibit 64b represents the available queue storage at the exit leg.

Exhibit 64 shows a shift in the cumulative queue distribution toward higher queues associated with the installation of the PHB. The largest effect is a significant reduction in the occurrence of zero queues in the post condition, which results in the large discrepancy at queue length equal to zero. However,

Exhibit 64. Cumulative distribution.



it is evident that very few long queues were observed in either the pre or post condition. With two lanes of storage, any total queue greater than two vehicles at the exit leg will cause some spillback into the circle, as shown by the dashed line. With the installation of the PHB, that proportion of maximum queues greater than two vehicles increased from 29.8% to 69.2%. However, the average queue is expected to be much lower, so that the overall effect of the PHB installation on vehicle queues is considered to be marginal. In fact, a determined yielder is likely to cause similar if not more delay to a driver waiting at the efficient PHB signalization scheme, as evident by some long queues observed in the pre study.

PHB Crosswalk Summary

In summary, the installation of the PHB or HAWK signal resulted in a large reduction in delay and elimination of O&M interventions for all study participants. The relative difference between pre and post studies was greatest for participants that experienced high delays in the pre condition since the PHB created a more uniform distribution of delay across participants. The PHB further reduced the overall number of pedestrian–vehicle interaction events, with far fewer rejected crossing opportunities. The reason for this was that drivers yielded (stopped at the light), thereby reducing the number of gaps encountered.

Most drivers complied with the signal indication, although there was evidence for both misunderstanding (waiting until "Blank" to proceed) and non-compliance (proceeding through a red signal) on the part of drivers. It is expected that these numbers may improve with additional public information material or enforcement. The installation of the PHB caused a marginal increase in vehicle queuing, although it is difficult to extrapolate that effect to higher-volume roundabouts. The analysis did confirm that queues caused by determined yielders can approach queues caused by the signal. Further, since many drivers did not proceed through the "Flashing Red," the post queues are longer than expected with the PHB scheme. The impact on queues is therefore expected to be reduced with improved public education and driver understanding of the PHB.

Overall, the installation of the PHB greatly increased the availability and utilization of crossing opportunities, which is reflected in a reduction in pedestrian delay. The PHB further reduced O&M interventions to zero, suggesting enhanced safety performance. Exhibit 65 summarizes these key metrics for the PHB evaluation.

But even given the improved pedestrian performance and the marginal vehicle impact, care needs to be taken extrapolating these results to higher-volume scenarios or roundabouts with different geometry. The PHB does appear to be a viable treatment for two-lane roundabouts, but it needs to be combined with pedestrian and driver education, as well as enforcement, to maximize its impact.

Exhibit 65. Summary performance statistics pre and post PHB installation.

Performance Measure	Pre	Post
Yield Availability*	29.7%	72.5%
Gap Availability*	28.7%	45.0%
Yield Utilization*	68.9%	95.0%
Gap Utilization*	88.2%	100.0%
85th Percentile Delay (s)	29.8	8.7
O&M Interventions	2.4%	0.0%

*Average of near and far lane

APPENDICES B THROUGH N

Appendices B through N are available on the TRB website (www.trb.org) by searching "NCHRP Web-Only Document 160".

Appendix B: Long List of Treatments
Appendix C: Team Treatment Survey
Appendix D: Details on Site Selection
Appendix E: Details on Treatment and Site Descriptions
Appendix F: Details on PHB Installation
Appendix G: Participant Survey Forms
Appendix H: Details on Team Conflict Survey
Appendix I: Details on Simulation Analysis Framework
Appendix J: Details on Accessibility Measures
Appendix K: Details on Delay Model Development
Appendix L: Details on Roundabout Signalization Modeling
Appendix M: Use of Visualization in NCHRP Project 3-78A
Appendix N: IRB Approval and Consent Forms

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation