Accelerating Roundabout Implementation in the United States – Volume I of VII

Evaluation of Rectangular Rapid-Flashing Beacons (RRFB) at Multilane Roundabouts

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U.S. Department of Transportation

Federal Highway Administration

Safe Roads for a Safer Future

Investment in roadway safety saves lives

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

FOREWORD

Since the Federal Highway Administration (FHWA) published the first *Roundabouts Informational Guide* in 2000, the estimated number of roundabouts in the United States has grown from fewer than one hundred to several thousand. Roundabouts remain a high priority for FHWA due to their proven ability to reduce severe crashes by an average of 80 percent. They are featured as one of the Office of Safety *Proven Safety Countermeasures* and were included in the *Every Day Counts 2* campaign for Intersection & Interchange Geometrics.

As roundabouts became more common across a wide range of traffic conditions, specific questions emerged on how to further tailor certain aspects of their design to better meet the needs of a growing number and diversity of stakeholders. The substantial work performed for this project – *Accelerating Roundabout Implementation in the United States* – sought to address several of the most pressing issues of National significance, including enhancing safety, improving operational efficiency, considering environmental effects, accommodating freight movement and providing pedestrian accessibility. This work represents yet another notable step forward in advancing roundabouts in the United States.

The electronic versions of each of the seven report volumes that document this project are available on the Office of Safety website at http://safety.fhwa.dot.gov/.

Michael S. Griffith
Director
Office of Safety Technologies

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This volume is first in a series of seven. The other volumes in the series are: Volume II – Assessment of Roundabout Capacity Models for the Highway Capacity Manual, Volume III – Assessment of the Environmental Characteristics of Roundabouts, Volume IV – A Review of Fatal and Severe Injury Crashes at Roundabouts, Volume V – Evaluation of Geometric Parameters that Affect Truck Maneuvering and Stability, Volume VI – Investigation of Crosswalk Design and Driver Behaviors, and Volume VII – Human Factor Assessment of Traffic Control Device Effectiveness. These reports document a Federal Highway Administration (FHWA) project to investigate and evaluate several important aspects of roundabout design and operation for the purpose of providing practitioners with better information, leading to more widespread and routine implementation of higher quality roundabouts.

This report presents results from a pedestrian accessibility study evaluating the effectiveness of Rectangular Rapid Flashing Beacons (RRFB) at multilane roundabouts in the U.S. The document summarizes data collection and analysis performed at 12 approaches at 7 multilane roundabouts in 5 states. The study applied an Accessibility Audit to all test locations, including an indicator study of blind pedestrian decision-making, a naturalistic driver yielding study, a vehicle free-flow speed study, a geometry audit, and a 12-hour traffic volume assessment. The findings from this study indicate that within the range of observed RRFB installations there are some likely relationships between traffic flow characteristics (volume and speed) and the availability of crossing opportunities in the form of gaps or yields. There is also some indication that the geometric configuration of a roundabout impacts its accessibility, either directly through obstruction of sight and hearing, or indirectly by allowing greater vehicular speeds. Overall, the results of these studies support the idea that RRFB-equipped multilane roundabouts can be accessible, but the roundabout geometry, vehicle speeds, and driver behavior have a strong influence on the overall accessibility of a site.</td></tr>
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CHAPTER 1. INTRODUCTION

This document summarizes data collection and analysis performed at 12 approaches at 7 multilane roundabouts in 5 states. At each roundabout approach, the entry and exit legs were evaluated separately, for a total of 24 data sets. The evaluation was conducted under the auspices of the Federal Highway Administration (FHWA) Strategic Initiative Project "Accelerating Roundabout Implementation in the United States," contract number DTFH61-10-D-00023. This report summarizes data collection and analysis for Task 2: Evaluation of Rectangular Rapid Flashing Beacons (RRFB). This report presents findings of the application of an *Accessibility Audit* at the 12 roundabout approaches.

The report first gives background on the accessibility concerns of multilane roundabouts, followed by a description of the general research methodology. Next, the report summarizes results for the following key performance measures: interventions, participant delay, and driver yielding behavior. It also describes the results of a correlation analysis between the performance measures and geometric attributes of the studied roundabouts. The report concludes with discussion of results and implications for practice. Three appendices are included that provide data collection protocol details, site details, and supplemental analysis details.

BACKGROUND

The question of the accessibility of multilane modern roundabouts has been the topic of significant U.S. research in recent years. Accessibility challenges of these intersections to pedestrians who are visually impaired or blind have been documented in a number of research efforts.[(1,2,3,4)] Draft language by the U.S. Access Board to establish *Public Rights of Way Accessibility Guidelines* (PROWAG) was proposed as early as 2002, with a Notice of Proposed Rulemaking (NPRM) by the U.S. Access Board, *Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way*, published in 2011. The NPRM calls for the provision of pedestrian-actuated signals at multilane crossings.[(5)] The NPRM allows for other treatments that "result in substantially equivalent or greater accessibility and usability" under section R102: Equivalent Facilitation. However, without clear guidance on performance metrics for equivalent facilitation, it can be challenging to identify and document alternatives to pedestrian-actuated signals at multilane crossings.

Variations of the standard pedestrian signal exist that can limit pedestrian-induced impacts on vehicular delay, including the Pedestrian Hybrid Beacon system (PHB), as documented in the 2009 Manual on Uniform Traffic Control Devices (MUTCD)[(6)] and the National Cooperative Highway Research Program (NCHRP) Report 674[(4)] at a multilane roundabout. The PHB is explicitly mentioned as a treatment alternative in the NPRM. However, other recently developed pedestrian crossing treatments and devices have the potential to achieve similar performance as a PHB, but at less cost and potentially lower impact to overall roundabout operations.

The rectangular rapid-flashing beacon (RRFB) system results in a significant and noteworthy increase in driver yielding compliance, according to research performed at mid-block pedestrian crossings in Florida[(7)], and has since been deployed in a number of states. "Active-when-present" beaconing systems were linked to higher yield compliance than continuously flashing beacons in national research on unsignalized pedestrian midblock crossings, although compliance levels were not as high as with a steady red indication.[(8)] That study pre-dated RRFB as a treatment alternative. A low rate of yielding to pedestrians is believed to be one of the contributing factors to accessibility concerns at many multilane roundabouts, and is one of the critical performance measures for accessibility identified in NCHRP Report 674.[(4)] Consequently, RRFB is a viable focus of research on accessibility, as it may improve yielding at a lower cost than a PHB or a pedestrian-actuated signal. In addition, solar-powered and wireless devices can typically be retrofitted to existing multilane roundabouts, if proven effective.

While strong evidence from research on RRFBs speaks to the potential of the RRFB as a yield-enhancing treatment, it is unclear (a) if a similar increase in yielding is achieved at multilane roundabouts as at mid-block pedestrian crossings, (b) if the treatment impact applies consistently to roundabouts with different volumes and geometries, (c) if the impacts apply equally to entry and exit legs, and (d) if the increase in yielding alone makes the crossing accessible to pedestrians who are blind. This project explored these questions through empirical research at various RRFB-equipped multilane roundabouts in the United States, with the goal of identifying performance thresholds for conditions in which the RRFB is an acceptable treatment to establish access for pedestrians who are blind.

CHAPTER 2. METHODOLOGY

Through the recently published NCHRP Report 674,[(4)] as well as involvement in a multiyear research grant by the National Eye Institute of the National Institutes of Health,[(9)] the foundation has been laid for accessibility research at modern roundabouts for pedestrians who are blind. That foundation includes defined performance measures, study methodologies, and examples of empirical evaluations of treatments at three roundabouts and two channelized turn lanes. However, prior research necessarily focused on identifying problems and developing basic protocols using a time- and labor-intensive pretest-posttest data collection protocol that required up to 20 field days per roundabout. The effort was extensive, but not adequate to develop clear guidance on what treatments may be appropriate under what conditions due to the range of roundabouts and treatments potentially available.

A significantly revised study protocol has since been developed and was applied in this project. This new protocol enables the team to evaluate a number of sites in a thorough and comprehensive, yet quick and cost-efficient, *Accessibility Audit*. The objective of such an audit is to evaluate the accessibility performance of a roundabout through the following five studies. Details for all studies are provided in the appendices.

1. <u>Crossing indicator study</u> with blind pedestrians at the crosswalk, who independently make crossing decisions while being accompanied by a Certified Orientation and Mobility Specialist (COMS). In the indicator study, the blind pedestrians raised their hand when they would begin crossing, rather than actually crossing, minimizing exposure in the actual travel lanes.

2. <u>Naturalistic yielding study</u> to strategically document the willingness of drivers to yield using randomly generated pedestrian crossing events at crosswalks. Pedestrians appear with and without a long white cane.

3. <u>Geometry audit</u> of the roundabout including inscribed diameter, design parameters (radii R1-R5 per the definitions in NCHRP Report 672[(10)]), crosswalk location relative to the circulating lane, detectable warnings, landscaping, and other features.

4. <u>Exploratory speed study</u> of free-flowing vehicles entering and exiting the roundabout to gain insight on the expected speed patterns in the vicinity of the crosswalk, and the effectiveness of design features (and the RRFB treatment) in reducing speeds.

5. <u>Twelve-hour volume assessment</u> to identify temporal fluctuations of traffic impacting accessibility, along with a study of gap availability over a full-day analysis horizon.

Similar in concept to a Pedestrian Road Safety Audit,[(11)] this standardized protocol was applied consistently to all sites in this research to allow for direct comparison between RRFB installations. Additional details on the methodology and data collection protocol for the five studies are presented in Appendix A.

Initially, the accessibility audit contained a sixth element that explored the ambient sound at the roundabout, as well as sound patterns during the trials. A sound measurement device was placed downstream of the crosswalk during the trials for the first three studied roundabouts (Olympia, WA, and Springfield, OR), and the sound patterns correlated with vehicular volumes and pedestrian decision-making. However, analysis results of these sound studies did not show a conclusive correlation with interventions. Consequently, the sound study was not used for the remaining sites.

SITE DESCRIPTION

The study protocol presented above (and described more fully in Appendix A) was applied to 12 two-lane approaches of 7 multilane roundabouts in Olympia, Washington, Springfield, Oregon, Oshkosh, Wisconsin, Carmel, Indiana, Albany, New York, and Davidson, North Carolina. An overview of all locations is shown in table 1, with additional details for the sites provided in Appendix B.

The analysis is on a "per leg" basis, where a leg is defined as either the entry or exit of any given approach at a roundabout. Overall, the experiment included 7 roundabouts, with a total of 12 approaches studied. This results in data for 24 legs: 12 entry legs and 12 exit legs. All legs have two lanes, except for two cases:

- The entry leg at the Fuller Road and Washington Avenue roundabout in Albany, New York, has a channelized turn lane in addition to the two entering lanes. The study was conducted at the channelized turn lane (CTL), denoted as "Entry*" in the data.
- The exit leg at the 4th Avenue and Olympic Street roundabout in Olympia, Washington, which is a single-lane exit, denoted as "Exit**" in the data.

Table 1. List of study locations.

Site No.	Leg No.	City	Intersection	Studied Leg	Exit/Entry	No. of Lanes
1	1	Albany, NY	Fuller Rd. at Washington Ave.	Fuller Rd. North	Entry*	One*
1	2	Albany, NY	Fuller Rd. at Washington Ave.	Fuller Rd. North	Exit	Two
1	3	Albany, NY	Fuller Rd. at Washington Ave.	Fuller Rd. South	Entry	Two
1	4	Albany, NY	Fuller Rd. at Washington Ave.	Fuller Rd. South	Exit	Two
2	5	Carmel, IN	Clay Terrace Blvd. (north RBT)	Clay Terrace Blvd. North	Entry	Two
2	6	Carmel, IN	Clay Terrace Blvd. (north RBT)	Clay Terrace Blvd. North	Exit	Two
3	7	Davidson, NC	Griffith St. at Harbour Place Dr.	Griffith St. East	Entry	Two
3	8	Davidson, NC	Griffith St. at Harbour Place Dr.	Griffith St. East	Exit	Two
3	9	Davidson, NC	Griffith St. at Harbour Place Dr.	Griffith St. West	Entry	Two
3	10	Davidson, NC	Griffith St. at Harbour Place Dr.	Griffith St. West	Exit	Two
4	11	Olympia, WA	Jefferson St. at 14th Ave. SE	14th Ave. East	Entry	Two
4	12	Olympia, WA	Jefferson St. at 14th Ave. SE	14th Ave. East	Exit	Two
5	13	Olympia, WA	Olympic St. W at 4th Ave. W	4th Ave. East	Entry	Two
5	14	Olympia, WA	Olympic St. W at 4th Ave. W	4th Ave. East	Exit	One
5	15	Olympia, WA	Olympic St. W at 4th Ave. W	Olympic St. North	Entry	Two
5	16	Olympia, WA	Olympic St. W at 4th Ave. W	Olympic St. North	Exit	Two
6	17	Oshkosh, WI	Jackson St. at Murdock Ave.	Jackson St. South	Entry	Two
6	18	Oshkosh, WI	Jackson St. at Murdock Ave.	Jackson St. South	Exit	Two
6	19	Oshkosh, WI	Jackson St. at Murdock Ave.	Murdock Ave. East	Entry	Two
6	20	Oshkosh, WI	Jackson St. at Murdock Ave.	Murdock Ave. East	Exit	Two
7	21	Springfield, OR	Pioneer Pkwy. at Hayden Bridge Rd.	Hayden Bridge Rd. East	Entry	Two
7	22	Springfield, OR	Pioneer Pkwy. at Hayden Bridge Rd.	Hayden Bridge Rd. East	Exit	Two
7	23	Springfield, OR	Pioneer Pkwy. at Hayden Bridge Rd.	Pioneer Pkwy. South	Entry	Two
7	24	Springfield, OR	Pioneer Pkwy. at Hayden Bridge Rd.	Pioneer Pkwy. South	Exit	Two

*Channelized turn lane. Fuller North in Albany, NY, has three entry lanes; one is a channelized right-turn lane.

PERFORMANCE MEASURES

The performance measures used for analyses in this research study are intervention rates, free-flow speed at crosswalk, yielding rate at crosswalks, and pedestrian delay. The definition of each of these performance measures and how they are measured are described below.

Percent Interventions

This performance measure was captured through a crossing indicator study with blind study participants. During the crossing indicator study, subject pedestrians independently made crossing decisions while being accompanied by a COMS. Two computer operators were also present to record a time-stamp log of the pedestrian-vehicle interaction event sequence. After each crossing trial, the COMS evaluated the safety of the crossing decisions and communicated the level of risk associated with the crossing decision to the computer operator with a hand signal. Risk was categorized into the three levels listed in table 2.

Table 2. Pedestrian risk levels and descriptions.

Pedestrian Risk Level	Description
Estimated Intervention	If the pedestrian had stepped into the roadway at the time the decision was made, the COMS <u>would have chosen to intervene by physically restraining the participant</u> to avoid a collision with an approaching vehicle.
Risky Event	If the pedestrian had stepped into the roadway at the time the decision was made, the COMS <u>may have chosen to intervene</u>, depending on driver reaction, pedestrian walking speed, or other considerations.
Safe Event	If the pedestrian had stepped into the roadway at the time the decision was made, the COMS <u>would not have chosen to intervene</u>, and would have let the crossing proceed.

The COMS evaluation did not include considerations that might be part of orientation and mobility instruction or an evaluation of the blind pedestrians' decisions. For example, some blind pedestrians made decisions to cross when there were loud vehicles traveling in the opposite direction, which would have masked the sound of any vehicle approaching. However, if that decision was made at a time when there was no vehicle approaching, or when vehicles had yielded, it was judged, in this research, as a "safe event." This limitation should be noted, as there were a number of decisions of this type observed. In addition, many times blind pedestrians would make a crossing decision when vehicles were yielding to them, but their comments indicated that they were not aware that there was a vehicle present at that point. Sometimes participants noticed and commented on the vehicle when it began moving after they began walking away from the crosswalk.

The computer operator also rated each crossing event for the same three risk categories prior to receiving the COMS indication. The two sets of risk judgments were therefore independently made by the expert observer and the COMS. The two independent intervention estimates were then compared to assure that the COMS rating represented an accurate assessment of the level of risk associated with the crossing decision (see Appendix C). The percent estimated interventions was defined as the frequency of “estimated intervention” events divided by the total number of decisions made by a participant. The remaining analysis focused on the estimated interventions (also referred to as percent interventions) and did not separately consider “risky events.”

Pedestrian Delay

Delay for each trial was measured in seconds and defined as the time from the start of the trial (when subject arrives at the crosswalk and is told to indicate when he/she would cross) to the moment that the participant indicated crossing by raising his or her hand. Delay was calculated as both average delay and 85^{th} percentile delay for all participants at a single crossing.

Free-Flow Speed at Crosswalk

The exploratory speed study of free-flowing vehicles entering and exiting the roundabout aimed to gain insight on the expected speed patterns in the vicinity of the crosswalk, and the effectiveness of design features (and the RRFB treatment) at reducing speeds. The speeds were captured with a radar speed measurement device for at least 30 free-flowing vehicles at the crosswalk. For the exit leg, the measurements were completed for single vehicles leaving the circle without being impeded by pedestrians or other vehicles. For the entry leg, the team also measured only vehicles that were not impeded by pedestrians or other vehicles in the circle (i.e., not having to yield the right-of-way upon entering the roundabout).

Yielding Rate at Crosswalk

This measure was captured through the naturalistic yielding study, where a member of the research team approached the crosswalk and a second team member recorded the driver’s choice to yield or not to yield. The objective of this study was to strategically document the willingness of drivers to yield using randomly generated pedestrian events at the crosswalk when pedestrians either used or did not use a long white cane.

CHAPTER 3. RESULTS

This section presents the results from the 24 studied roundabout approaches (12 entries and 12 exits). The analysis initially presents a summary of key performance measures, and then correlates performance measures with other variables such as free-flow speed and geometric attributes of the roundabouts.

SUMMARY OF PERFORMANCE MEASURES

The key performance measures in the crossing indicator study are the rate of estimated interventions, participant delay, and the rate at which drivers yielded to pedestrians at the RRFB-equipped roundabout approaches. The intervention rate was estimated here because no actual street crossings were performed by the blind study participants. Consequently, the intervention rate refers to the number of times the COMS would have intervened divided by the total number of trials. The estimated intervention rate was further confirmed by an independent expert observer. Yield rate results shown are from the naturalistic yielding study for the condition of a sighted pedestrian (no cane) who activated the RRFB.

Five to seven blind study participants made crossing decisions at each of the roundabout approaches for both entry and exit legs. Each participant made multiple crossing decisions (typically 10) at each approach, resulting in a total sample size of 50 or more observations per leg studied. Table 3 summarizes the key data findings for estimated interventions, participant delay, and driver yielding rates at the 12 studied approaches.

Table 3. Summary of key findings.

Site No.	City, State	Approach	Entry/Exit	No. Est. Inter.	Avg. Est. Inter. (%)	Avg. Part. Delay	85th Percent-tile Part. Delay	Max Part. Delay	Yielding Rate+ (%)
1	Albany, NY	Fuller North	Entry (*n*=59)**	8	13.6	9.8	24.4	150.5	36.0
2	Albany, NY	Fuller North	Exit (*n*=60)	13	21.7	28.2	70.4	129.1	0.0
3	Albany, NY	Fuller South	Entry (*n*=60)	1	1.7	8.5	19.1	130.4	39.0
4	Albany, NY	Fuller South	Exit (*n*=62)	8	12.9	10.2	31.6	66.0	11.0
5	Carmel, IN	Clay Terrace	Entry (*n*=52)	2	3.8	16.4	26.7	81.9	60.0
6	Carmel, IN	Clay Terrace	Exit (*n*=50)	2	4.0	13.3	19.1	79.0	61.0
7	Davidson, NC	Griffith East	Entry (*n*=23)	1	4.3	9.1	13.9	25.8	96
8	Davidson, NC	Griffith East	Exit (*n*=23)	0	0.0	10.1	16.8	19.7	80
9	Davidson, NC	Griffith West	Entry (*n*=23)	0	0.0	14.2	23.0	62.0	100
10	Davidson, NC	Griffith West	Exit (*n*=24)	2	8.3	10.7	20.4	35.1	96
11	Olympia, WA	14th	Entry (*n*=42)	3	7.1	2.3	3.4	6.5	95.0
12	Olympia, WA	14th	Exit (*n*=42)	1	2.4	2.9	4.6	10.2	100.0
13	Olympia, WA	4th	Entry (*n*=45)	1	2.2	4.3	6.5	15.7	89.5
14	Olympia, WA	4th	Exit (*n*=35)*	1	3.0	2.8	4.8	7.6	97.0
15	Olympia, WA	Olympic	Entry (n=45)	3	6.7	4.5	6.9	17.6	94.0
16	Olympia, WA	Olympic	Exit (*n*=45)	0	0.0	2.9	4.8	10.1	94.0
17	Oshkosh, WI	Jackson	Entry (*n*=48)	1	2.1	12.4	20.7	48.3	83.0
18	Oshkosh, WI	Jackson	Exit (*n*=50)	8	16.0	17.3	27.5	69.2	20.0
19	Oshkosh, WI	Murdock	Entry (*n*=40)	0	0.0	13.1	19.5	32.7	90.0
20	Oshkosh, WI	Murdock	Exit (*n*=40)	6	15.0	17.0	26.7	62.0	20.0
21	Springfield, OR	Hayden	Entry (*n*=45)	1	2.2	8.9	12.6	53.9	100.0
22	Springfield, OR	Hayden	Exit (*n*=41)	5	12.2	9.3	11.4	31.1	100.0
23	Springfield, OR	Pioneer	Entry (*n*=48)	2	4.2	5.7	8.3	36.6	90.0
24	Springfield, OR	Pioneer	Exit (*n*=44)	5	11.4	10.4	15.1	37.0	64.0

** This exit is only a single lane.*

*** This entry is a channelized turn lane.*

+ Percent Yielding Rate was estimated from 30 trials in naturalistic yielding study for sighted pedestrian with RRFB activated.

Estimated interventions ranged widely across the studied locations, with 0.0 percent to 21.7 percent of trials resulting in an intervention. In comparison, a prior evaluation of an RRFB in Oakland County, Michigan, showed 7.5 percent and 23.8 percent estimated intervention rates at a two-lane entry and exit without the RRFB, respectively. After the RRFB was installed, intervention rates were 0.0 percent and 16.4 percent. A more-detailed evaluation of interventions is presented below.

The results of the delay analysis showed that the average delay for pedestrians who are blind varied from 2 s to 28 s, with 85th percentile delays of up to 70 s to cross a two-lane exit leg. In comparison, the two-lane roundabout approach delays with RRFB measured in the prior Oakland County, Michigan, study for blind participants were 17.1 s and 18.8 s for entry and exit, respectively.

The results in table 3 also show differences in yielding. Some approaches showed high yielding rates to pedestrians, varying from 80 percent to 100 percent, while other approaches had much lower yielding, below 40 percent. In comparison, multilane roundabouts across the country showed an average yielding rate of 67 percent and 55 percent at entry and exit, respectively.(12)

In the following sections the results for the three performance measures of interventions, delay, and yielding are described in more detail.

Percent Interventions by Leg

Figure 1 shows the percent of interventions by leg (entry or exit) for the twelve studied approaches. The chart includes the intervention results from table 3 sequenced from highest to lowest. Exit legs are shown in black, and entry legs shown in gray. Data for the channelized turn lane site* and the single-lane exit** are also included.

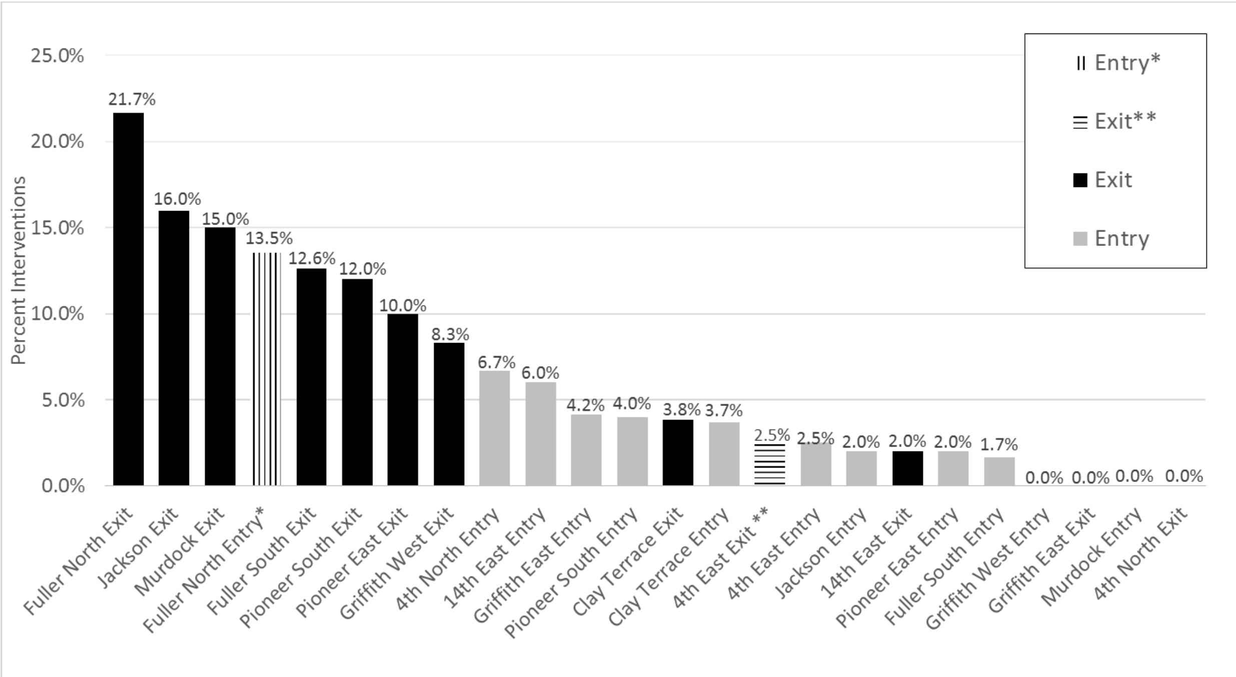

Figure 1. Chart. Percent interventions by leg for all study locations.

As shown in figure 1, exit legs tend to have a higher percent interventions than entry legs. Eleven out of twelve entries had less than 10 percent interventions, and nine out of twelve had intervention rates less than 5 percent. Only one entry leg showed more than 10 percent interventions (13.5 percent), which is the entry leg of the Fuller Rd. at Fuller and Washington roundabout in Albany, New York. This entry leg is the channelized right-turn lane of a three-lane approach. The 13.5-percent intervention rate is the result of an average of five participants with one intervention each (10 percent) and one participant with three interventions (30 percent). The Murdock Ave. entry leg in Oshkosh, Wisconsin, an entry leg with a relatively high amount of deflection (as discussed in the next section), had an intervention rate of zero percent, as did the Griffith West entry in Davidson, North Carolina.

For the exit legs, only 5 out of 12 had less than a 5-percent intervention. Three of the five exit legs with low intervention rates are located in Olympia, Washington, where the team noted generally high driver yielding compliance. These locations in Olympia, Washington, are the 4th St. East exit leg, the 14th St. exit leg, and the 4th St. North exit. The 4th St. North exit leg in Olympia, Washington, had a zero-percent intervention, and features a steep uphill roadway below the studied crosswalk that slows traffic at the crosswalk. The fourth exit leg with a low intervention rate is the Clay Terrace Blvd. exit in Carmel, Indiana, which is in a low-speed shopping center environment. The fifth exit leg was located in Davidson, North Carolina, which was found to be another community with generally high yield compliance and high pedestrian expectancy by drivers.

Six of the remaining seven exit legs show 10 percent or more interventions. The last exit, another exit in Davidson, North Carolina, had an 8.3-percent interventions. The difference between this exit and the second exit studied at this location (with zero interventions) may be at least partly attributed to vehicles accelerating toward a freeway interchange at the west exit, while decelerating to a small town environment (and a second roundabout) at the east exit. In addition, visibility of the exit crosswalk was not good for drivers in the circle due to vertical roadway alignment and trees. The four exit legs with the highest intervention rates are located at the Albany, New York, and Oshkosh, Wisconsin, sites. Both of those locations feature high deflection for vehicles at the entry (fastest path radii less than 200 ft), and relatively low deflection at exits, with exit radii above 400 ft. This may have contributed to elevated speeds and lower yielding at these locations. The effect of radius and resulting speed impacts are further explored below.

Percent Interventions by Radius and Degree of Curve

Figure 2 shows the percentage of interventions as a function of the radius of curve immediately upstream of the crosswalk, and figure 3 shows the percentage of interventions as a function of the degree of curvature. The radius was measured from design drawings or aerial photographs. The degree of curvature, C, is a transformation of the radius term, and is calculated by $C = 18000 / (Pi*Radius)$. A higher radius (flatter curve) corresponds to a smaller degree of curvature, and a small radius corresponds to a high degree of curvature. The quantities of radius and degree of curve are proportional, and thus are expected to lead to similar conclusions. They are both included, as different roundabout designers may prefer to work with one over the other.

A tangential exit with an infinite radius has a degree of curvature of zero. The range of studied radii ranged from as low as 61 m (200 ft) to well above 1,500 m (5,000 ft), and the corresponding degree of curve values ranged from greater than 55 to close to zero.

The chart shows entry legs on the left and exit legs on the right. Two special cases—the channelized turn lane at entry and the single-lane exit—have been highlighted in darker gray to distinguish them from the standard two-lane approaches. The chart also shows the percentage of interventions for entry (gray dashed line) and exit (black solid line). The approaches have been sequenced from shortest to longest radius within the entry or exit groups. The exit radii for the Fuller Road roundabout in Albany, New York, were measured to be near tangential, and exceeded 1,500 m (5,000 ft). They are plotted as a 305 m (1,000 ft) radius on the chart for readability. For the degree of curvature, the true values are plotted.

Overall, it can be concluded from figure 2 that entry legs have generally smaller radii (tighter curves) than exit legs. There further appears to be a correlation between increasing percent interventions and increasing radii for both entry and exit. The highest percent interventions occurred at the very large exit radii, and even for entry legs, sites with larger radii appear to have higher percent interventions. Figure 3 shows the same data for degree of curvature with reversed trends as expected. A larger degree of curvature is evident for entry legs than exit legs. For each category, a larger degree of curvature appears to be correlated with a lower rate of interventions.

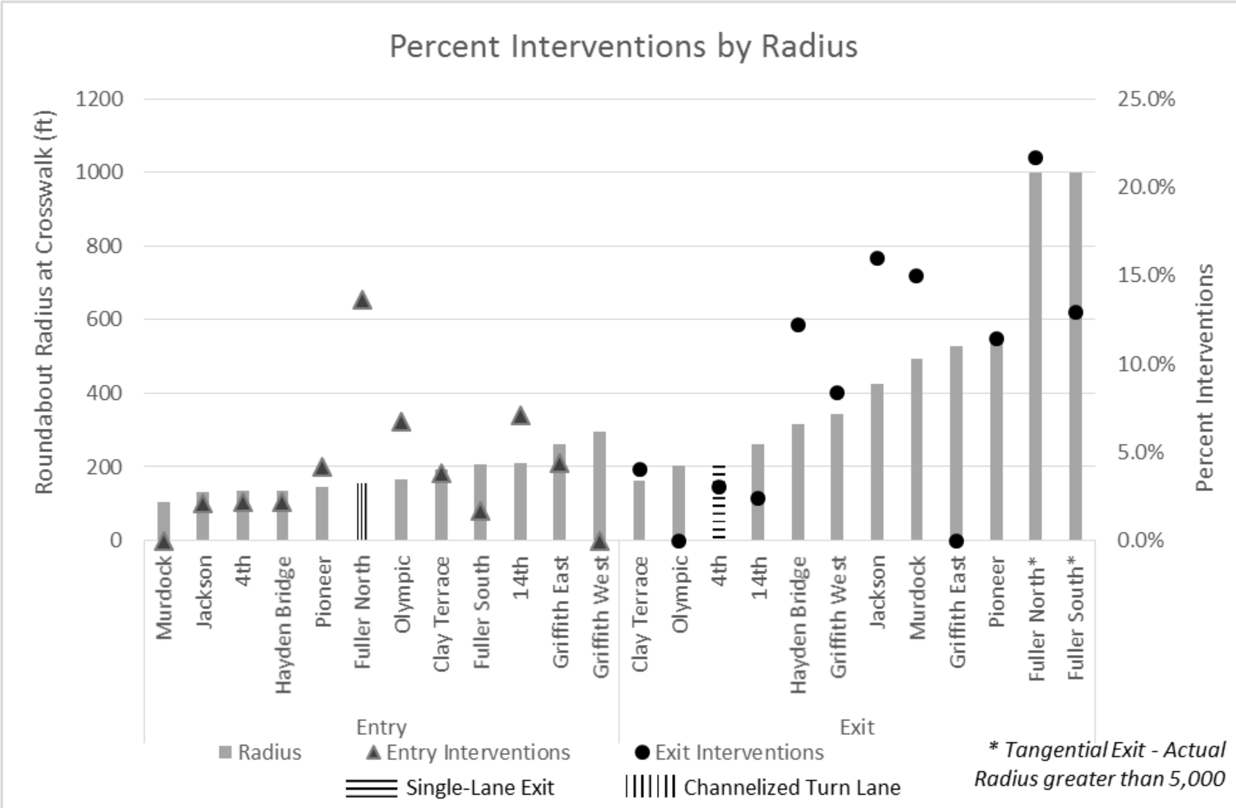

Figure 2. Chart. Percent of interventions as a function of radius of curvature at crosswalk.

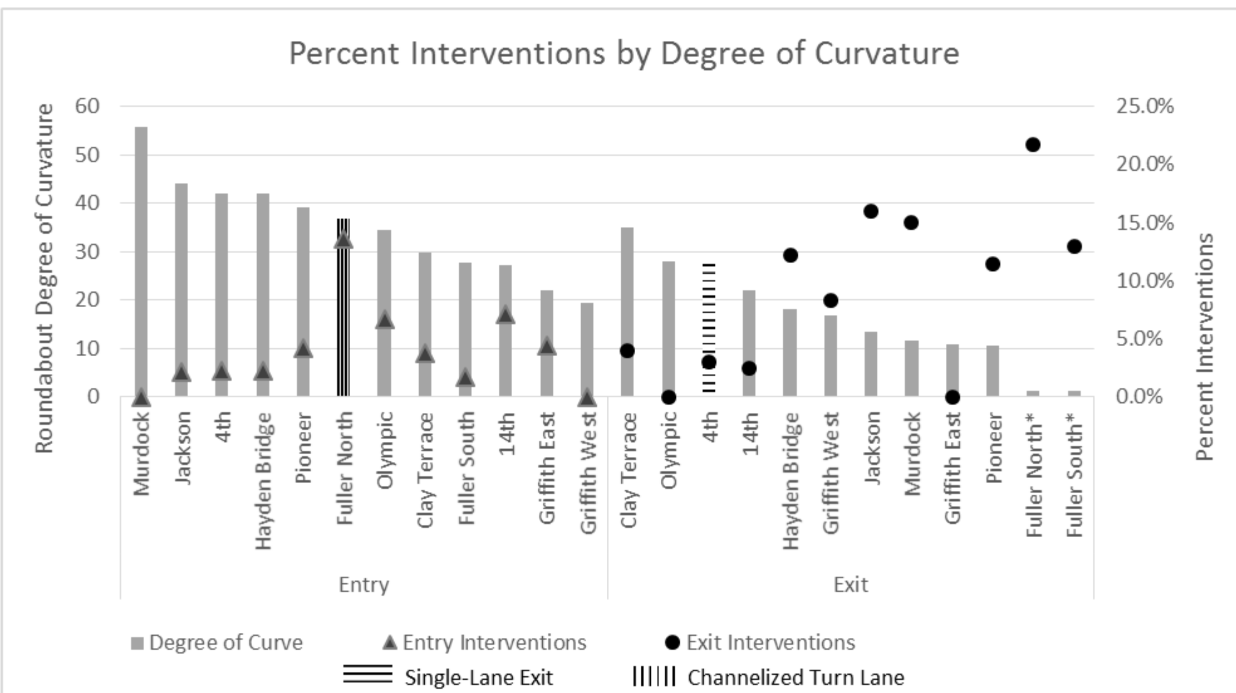

Figure 3. Chart. Percent of interventions as a function of degree of curvature at crosswalk.

A key exception to this trend appears to be the Davidson, North Carolina, roundabout. The site has a relatively large radius exit of more than 152 m (500 ft) at the Griffith East exit, which had zero interventions. Closer evaluation of the site showed relatively low vehicle speeds at that exit, despite the high radius, likely because drivers using this exit transition into a small town and pedestrian-focused environment, and because a second roundabout lies a few hundred feet downstream. In addition, drivers approaching from the west have a good view of the entire roundabout and the crosswalks (and RRFBs) on the east leg. The observation was similar for the west entry at this same roundabout, which also had zero interventions, despite having the largest entry radius studied. This entry is along the same travel path at the east exit. Interestingly, the reverse direction (east entry and west exit) had more interventions despite having smaller radii. Driver perception and expectation may again be a contributing factor here, with drivers leaving the small town community (and the expectation of pedestrian traffic), while accelerating toward a freeway interchange just west of the studied roundabout. This suggests that while geometric characteristics appear to show an effect, local context, driver culture, and visibility of the crossing appear to be equally (if not more) important for pedestrian safety and accessibility of a site.

The same data are shown in figure 4 as a scatterplot, showing percent interventions as a function of the degree of curvature for entry (gray triangles) and exit (black circles). For the entry leg data, the channelized turn lane site has been removed from the plot, as it represents a generally different geometric configuration than the other entry legs.

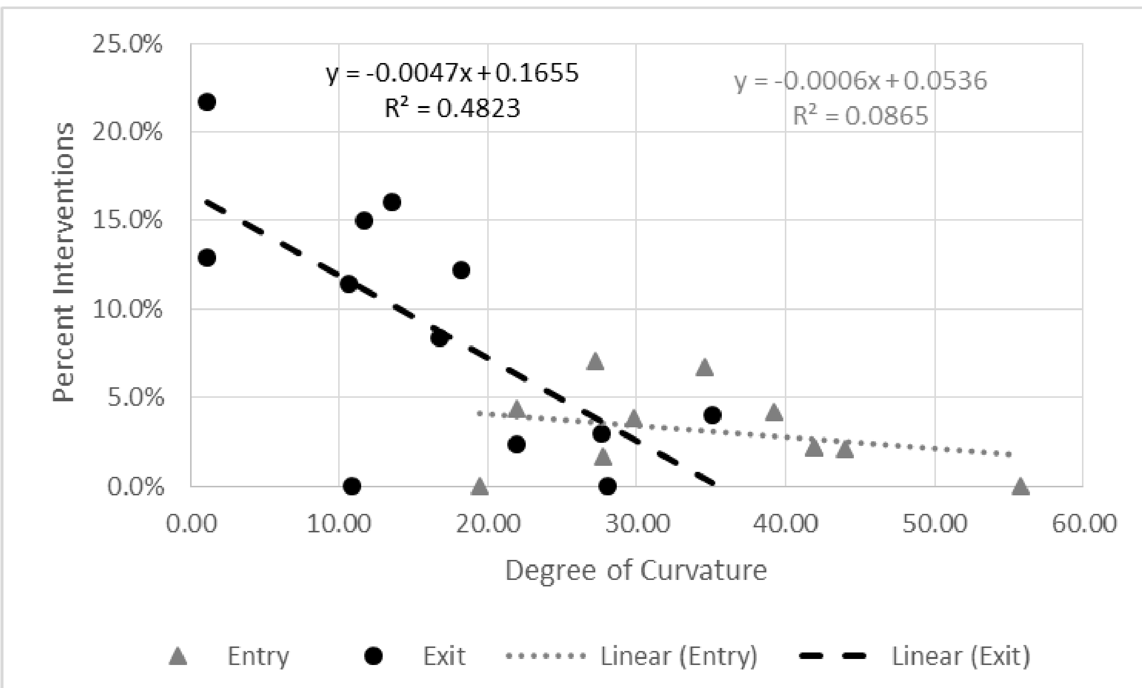

Figure 4. Graph. Percent intervention as a function of degree of curvature (all sites).

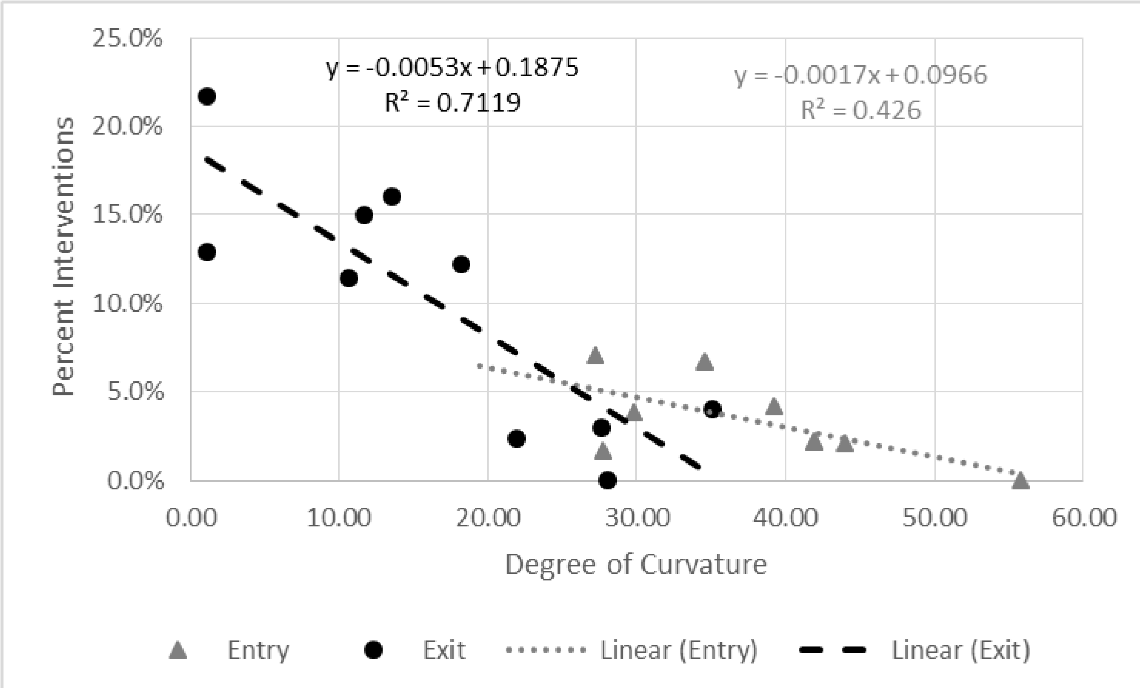

Figure 5. Graph. Percent intervention as a function of degree of curvature (Davidson, NC, site removed).

The scatterplot presented in figure 4 shows correlation between interventions and the radius of curve for the exit with an R-squared value of 0.4823. The Davidson, North Carolina, site is an outlier in this relationship as discussed above. As shown in figure 5, if the outlier is excluded, the R-squared of the relationship increases to 0.7119. Without the Davidson site, there was also a relationship for the entry leg between degree of curvature and interventions, but at a somewhat lower R-squared (0.4260). With inclusion of the Davidson site as shown in figure 4, this relationship is weaker, with an R-squared value of 0.0865.

In figure 5, the slope parameter for entry is less than that for exit, suggesting a lower sensitivity of percent intervention to degree of curvature for entry than for exit. For the exit leg, the regression line has an intercept of 18.8 percent intervention for a degree of curvature close to zero. A very low degree of curvature represents a very large radius or a near-tangential exit configuration. With increasing degree of curvature, the average rate of intervention decreases at a rate of 0.53 percent for each degree of curve. Consequently, an increase in 10 degrees in curvature is expected to reduce the intervention rate by more than 5 percent.

For the entry leg, the trend of decreasing intervention rate with increasing degree of curvature is also evident. With an intercept of 9.7 percent the base intervention rate at entries is lower than at exits, likely being attributable to improved lines of sight and vehicles generally decelerating at the entry while accelerating at the exit. The slope parameter of 0.0017 suggests a 0.17 percent decrease in interventions for each one degree increase in curvature. It should be noted that the smallest entry degree of curvature observed in this study was approximately 27 degrees, with an intervention rate of 6.0 percent.

Free-Flow Speed as a Function of Degree of Curve

Figure 6 shows the field-measured free-flow speed at the crosswalk as a function of the degree of curvature at the crosswalk. The free-flow speed was determined from a sample of 30 free-flowing vehicles without pedestrians present. No circulating speeds were measured. The degree of curvature was estimated from the radius, which was measured from design drawings or aerial photographs. Figure 6 distinguishes entry leg (gray triangles) and exit leg (black circles) events.

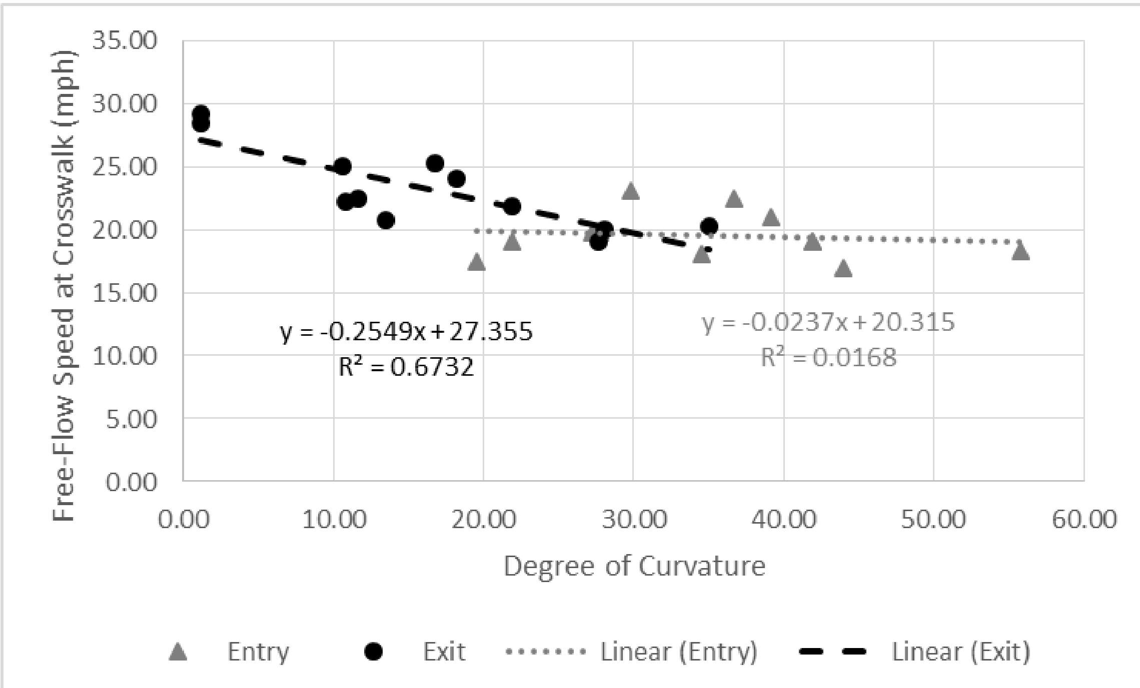

Figure 6. Graph. Free-flow speed at crosswalk as a function of degree of curvature.

Figure 6 exhibits a decrease in free-flow speed as a function of degree of curvature at the exit crosswalks, but no relationship for the entry crosswalks was studied. Note that a larger degree of curvature denotes a smaller radius. The exit degree of curvature tends to be smaller than entry (indicating a larger radius), and the exit free-flow speeds tend to be higher than the speeds at entry. The slope and R-squared of 0.6732 for the exit leg suggests a correlation of free-flow speed to the degree of curvature at the exit leg. For the entry, the relationship is less pronounced, with speeds being relatively constant across the sites, suggesting that drivers may also anticipate the possibility of yielding to conflicting traffic and the need to negotiate geometry within the roundabout.

Percent Yielding by Free-Flow Speed

Figure 7 shows the percentage of drivers yielding as a function of free-flow speed measured at crosswalks. The yield percentage was determined through the naturalistic yielding study; the speed measurements were obtained with a radar device during free-flow conditions in the absence of any pedestrians. The chart shows entry legs in gray triangles and exit legs in black circles. The two exceptional cases—the channelized turn lane at entry and the single-lane exit—were excluded from this analysis as to not bias the trend line results.

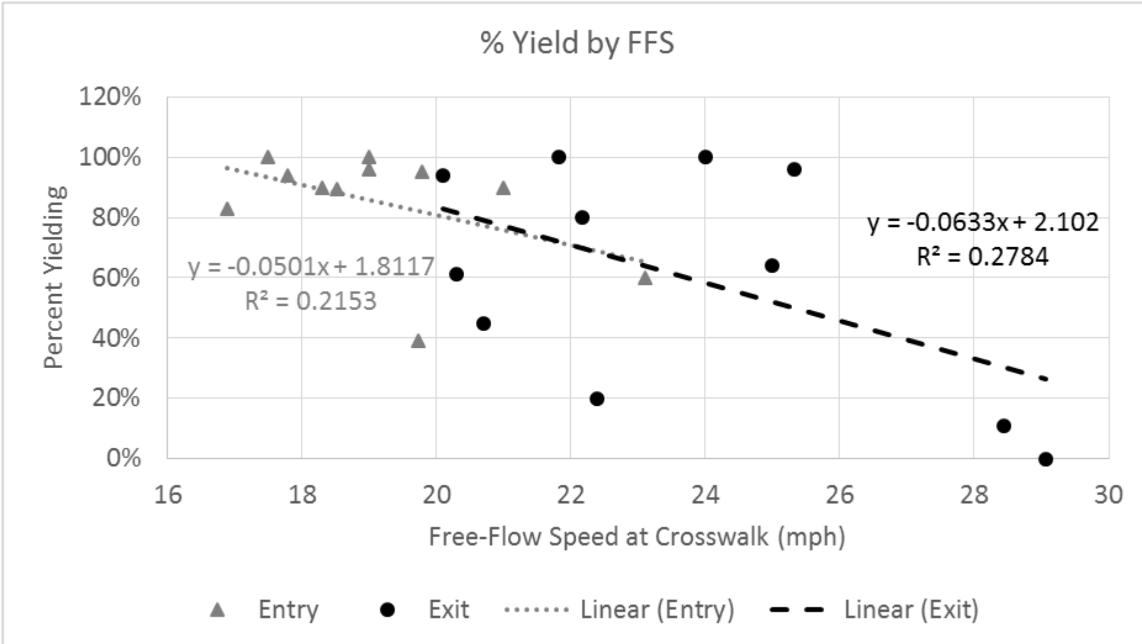

Figure 7. Graph. Percent yielding as a function of free-flow speed at crosswalk (mph).

Figure 7 shows an inverse correlation between percent yielding and speed for entry and exit. Exit speeds are generally higher than entry speeds. Figure 7 shows that the speed effect (slope of the line) is strikingly similar for both entry and exit legs. The corresponding R-squared values for entry and exit are 0.2153 and 0.2784, respectively, suggesting that while speed is a factor impacting yielding, it is clearly not the only explanatory factor. In other words, the dispersion in the data makes it difficult to identify clear relationships, although general trends are observable.

Percent Interventions by Free-Flow Speed

Figure 8 shows the percentage of interventions as a function of free-flow speed measured at the crosswalk (sample of 30 free-flowing vehicles without pedestrian presence). The chart shows entry legs in gray triangles and exit legs in black circles. The channelized turn lane at entry and the single-lane exit were excluded from this analysis.

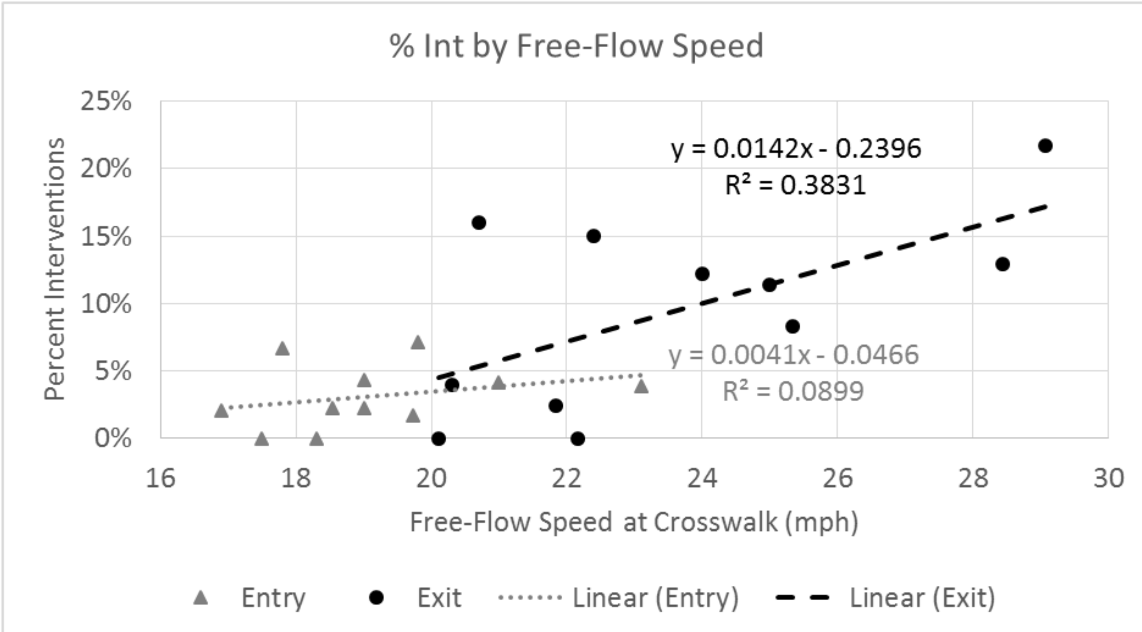

Figure 8. Graph. Percent intervention as a function of free flow speed at crosswalk.

According to the data presented in figure 8, there is a positive correlation between percent intervention and speed for exits, and suggests a weak positive relationship for entries. Exit speeds and percent interventions are generally higher than entry speeds and percent interventions. Figure 8 also shows that the effect of speed (slope of the line) on percent intervention is more than three times as large for exits, suggesting that exit interventions are more sensitive to speed than entry interventions. The R-squared values for entry and exit are 0.0899 and 0.3831, respectively, indicating a stronger correlation at exit than entry.

The observed percent intervention behavior is different below about 35 km/h (22 mph) than it is above that speed. For sites with free-flow speed below this threshold, all but one location exhibited less than 10 percent interventions, and 12 out of 14 had less than five percent interventions. For sites with a free-flow speed greater than 35 km/h (22 mph), five out of seven had more than 10 percent interventions, and six out of seven had more than five percent interventions. This finding does not imply that all crosswalks with free-flow vehicular speeds greater than 35 km/h (22 mph) are inaccessible, nor that all crosswalks with free-flow speeds less than this value are accessible. Other research[12] suggests that in some cases factors such as ambient noise and the visibility of pedestrians, the crosswalk, and associated signs and markings may have a greater influence than vehicular path radii and free-flow speeds. Nonetheless, it appears designs with free-flow exit speeds greater than 35 km/h (22 mph) have a higher likelihood of being inaccessible than those with lower vehicular path radii and free-flow speeds.

Percent Interventions by Percent Yielding

Figure 9 shows percent intervention as a function of the percentage of drivers yielding. The yield percentage was determined through the naturalistic yielding study, and the intervention rate was obtained from the crossing indicator study. The chart shows entry legs in gray triangles and exit legs in black circles. The channelized turn lane at entry and single-lane exit were excluded from this analysis.

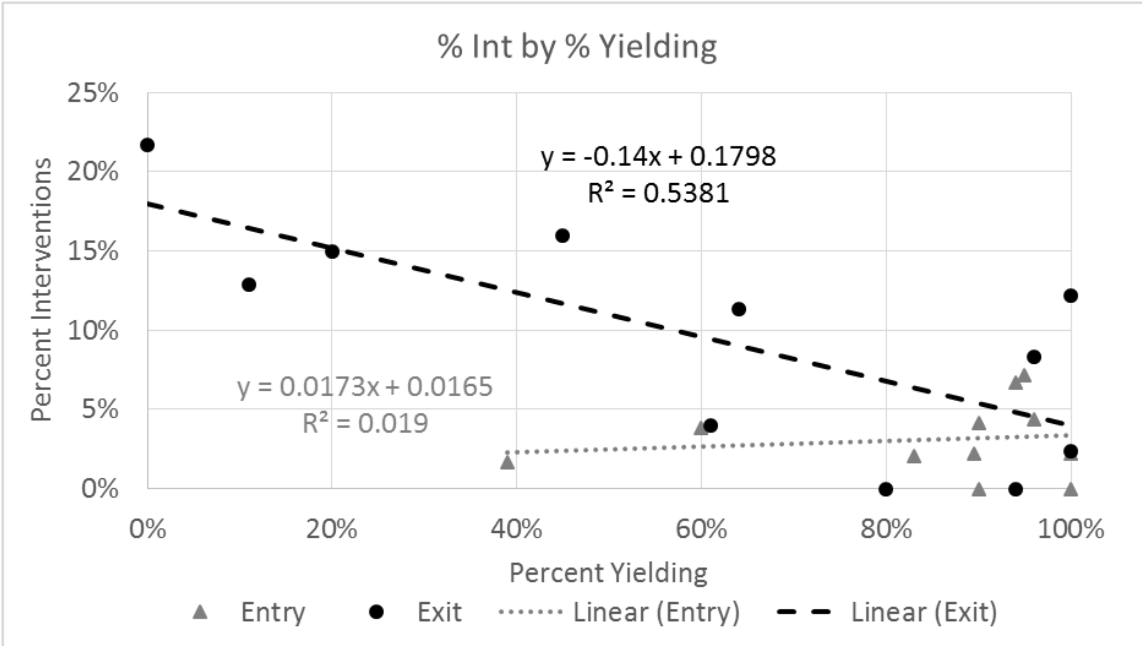

Figure 9. Graph. Relationship between percent interventions and percent yielding.

Figure 9 suggests an inverse correlation between percent interventions and yielding for exits. The R-squared value is 0.5381, showing a strong statistical correlation between the two values, with lower interventions rates observed at sites where drivers' yielding rate is higher.

The figure does not show a clear correlation between percent interventions and yielding for entry legs, given a very low R-squared value. Specifically, the entry approaches show a non-zero percent interventions even at very high yielding rates. This may be because multilane sites with high yielding rates might have one heavily utilized lane with high yield rates, resulting in queued vehicles blocking the line of sight between pedestrians and drivers in the less-utilized lane. Thus, drivers in the less-utilized lane may have low yield rates. This situation may then create multiple threat events to pedestrians, noted at several of the two-lane entry sites in field observations, especially at sites that exhibited imbalanced lane utilization.

The yielding rate data were collected in the naturalistic yielding study non-concurrently with the indicator study. The entry leg with the highest yield rate also had the highest percent interventions. A potential treatment described in the literature, to counteract the potential for multiple-threat events at the entry leg, is the used of advanced yield lines. However, none of the studied sites had that treatment in place.

Pedestrian Delay By Leg (Sorted)

The average, 85^{th}-percentile, and maximum pedestrian delay per participant by leg are shown in figure 10. The chart is ordered from highest to lowest average delay, with exit legs shown in black, and entry legs shown in gray. The channelized turn lane site (dashed) and the single-lane exit (black dotted) are also highlighted.

Overall, the figure shows that exit legs appeared to have longer average pedestrian delay than entry legs. Nine out of the 12 exits have more than 10 s of average delay per pedestrian. Only two exit legs had less than 5 s average delay, and one of them was the single-lane exit. Eight out of 12 entry legs have less than 10 s delay, and three have less than 5 s delay per pedestrian.

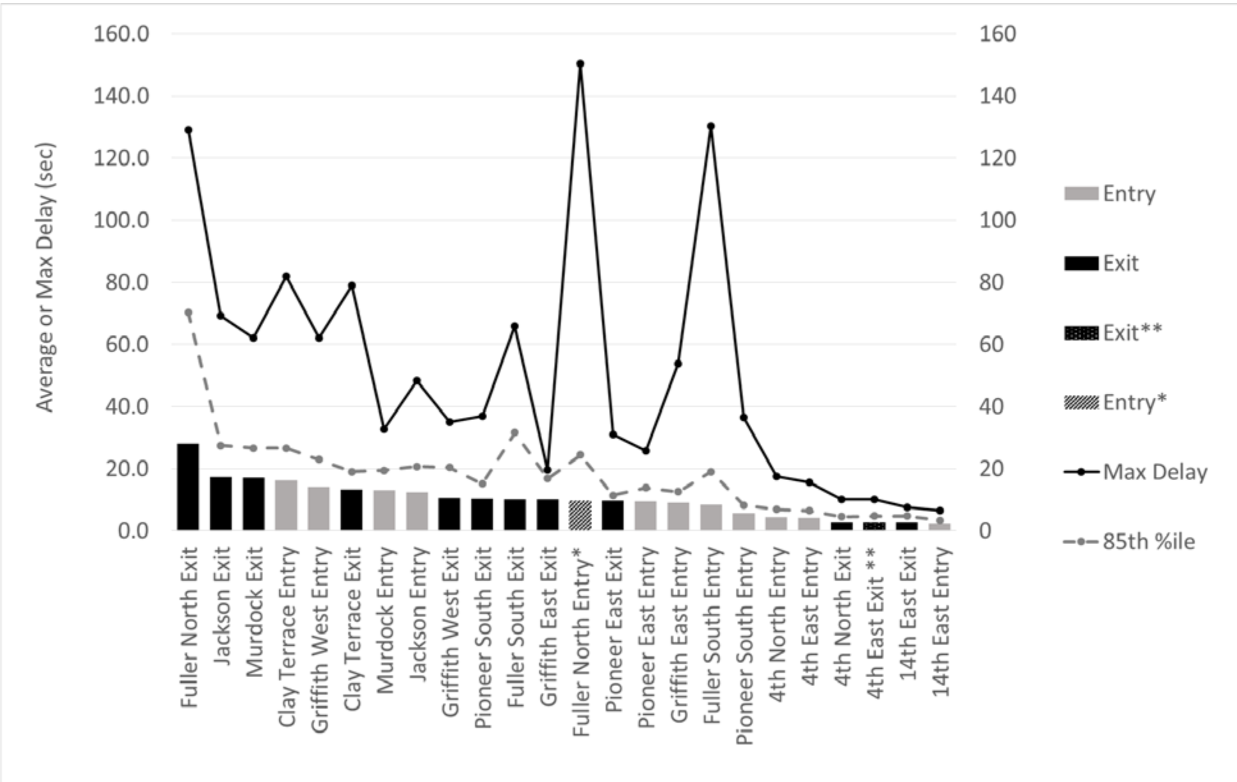

Figure 10. Chart. Average and maximum pedestrian delay by leg.

In addition to the average delay, the 85^{th}-percentile and maximum delay per participant are plotted. Those two measures generally show a similar trend as the average delay, and decline from left to right in the figure, but some outliers are evident. In particular, the maximum and 85^{th} percentile delays for the two entry legs at the Albany, New York, site have very high 85^{th} percentile and maximum delays. Given the relatively low average delays at those roundabouts, this suggests that some participants experienced very high delays at these locations, while others had little to no delay. A high 85^{th}-percentile delay (relative to the trend in average) is also evident at the Albany, New York, southern exit. A likely explanation for this is a time-of-day effect, where delays are high during peak periods and lower at low-volume, off-peak periods.

Apart from these outliers, the 85^{th}-percentile delay is generally 1.5 to 2.5 times greater than the measured average, while the maximum delay is three to six times greater than the average. The variation in delay is likely because participants have varying abilities to discern when it is safe to cross, and because traffic patterns change throughout the day.

Delay and Percent Intervention Comparison

Table 4 shows a side-by-side comparison of percent intervention and the average delay per leg. The table is ordered by rank of percent intervention, with the first rank being the leg with the highest recorded rate of percent intervention.

Table 4. Comparison of delay and percent intervention for each study approach.

Label	Exit/Entry	Average Percent Intervention (%)	Average Delay (s)	Intervention Rank	Delay Rank
Fuller North Exit	Exit	21.7	28.2	1	1
Jackson Exit	Exit	16.0	17.3	2	2
Murdock Exit	Exit	15.0	17.0	3	3
Fuller North Entry*	Entry*	13.6	9.8	4	13
Fuller South Exit	Exit	12.9	10.2	5	11
Pioneer East Exit	Exit	12.2	9.3	6	14
Pioneer South Exit	Exit	11.4	10.4	7	10
Griffith West Exit	Exit	8.3	10.7	8	9
14th East Entry	Entry	7.1	2.3	9	24
4th North Entry	Entry	6.7	4.5	10	19
Griffith East Entry	Entry	4.3	9.1	11	15
Pioneer South Entry	Entry	4.2	5.7	12	18
Clay Terrace Exit	Exit	4.0	13.3	13	6
Clay Terrace Entry	Entry	3.8	16.4	14	4
4th East Exit **	Exit**	3.0	2.8	15	23
14th East Exit	Exit	2.4	2.9	16	21
4th East Entry	Entry	2.2	4.3	17	20
Pioneer East Entry	Entry	2.2	8.9	18	16
Jackson Entry	Entry	2.1	12.4	19	8
Fuller South Entry	Entry	1.7	8.5	20	17
Murdock Entry	Entry	0.0	13.1	21	7
Griffith West Entry	Entry	0.0	14.2	22	5
4th North Exit	Exit	0.0	2.9	23	22
Griffith East Exit	Exit	0.0	10.1	24	12

According to table 4, the three approaches with the highest intervention are also the same three approaches with the highest average delay per subject. The remaining approaches with more than a 10-percent intervention have delays of around 10 s. Several approaches with more than 10 s average delays have intervention less than five percent. These approaches are Clay Terrace entry with 16.4 s delay and a 3.7-percent interventions, Clay Terrace exit with 13.3 s delay and a 3.8-percent interventions, Murdock entry with 13.1 s delay and a zero-percent interventions, and

Jackson St. entry with 12.4 s delay and 2.0-percent interventions. Each of these locations had upstream signals that resulted in some platoons of traffic. One potential explanation is that participants were waiting for large gaps at these approaches ("all-quiet periods"), which would explain the higher delay, but may have helped reduce interventions.

Figure 11 plots the relationship between interventions and delay for the various approaches. The relationship is very strong for exit legs (black dashed line) with an R-squared value of 0.6751. The relationship indicates increasing delay with increasing percent intervention; the exits with the highest rates of interventions were also those exit legs with the shortest delay. For entry legs, the trend is the opposite; exits with high percent interventions tended to also have the shortest delays, but that trend is weak, with an R-squared value of 0.1152. The differing trends show that blind participants experienced more challenges at exit legs compared to entry legs.

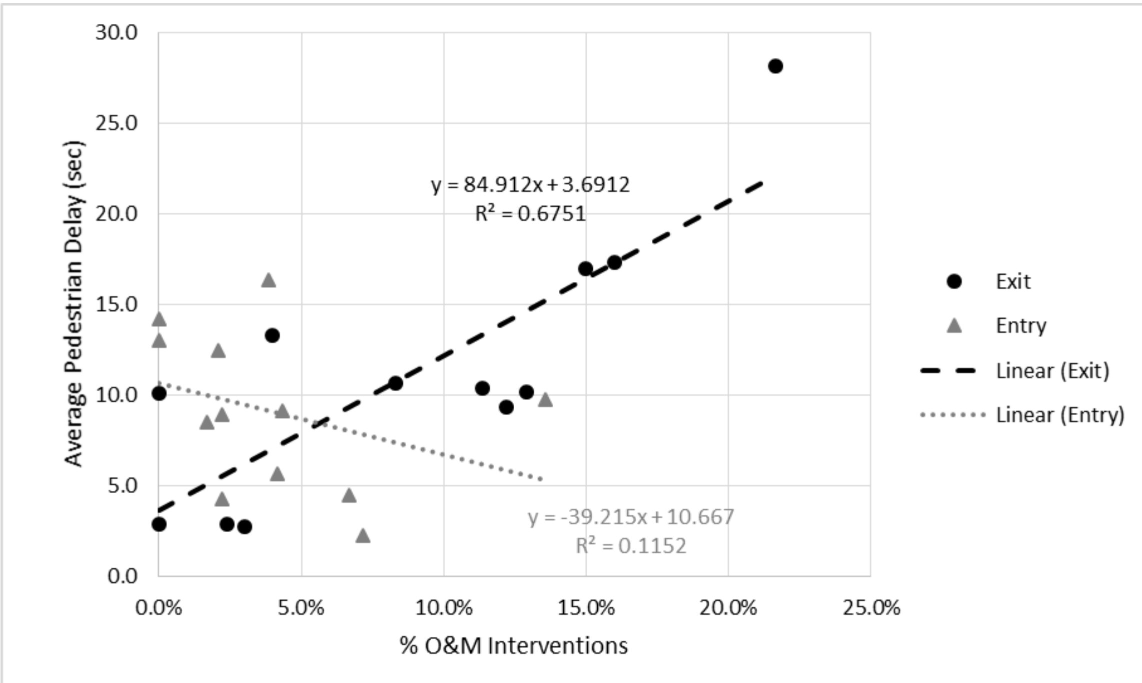

Figure 11. Graph. Percent interventions and delay correlation.

Percent Interventions by Traffic Volume by Approach

This section evaluates percent interventions as a function of traffic volume on the conflicting leg (lanes closest to the participant), as shown in figure 12. The graphs distinguish entry legs (gray triangles) and exit legs (black circles), and include a linear trend line fit to the data. The single-lane exit and channelized turn lane are excluded from this analysis. The Davidson site is also excluded, as no traffic volume data were available.

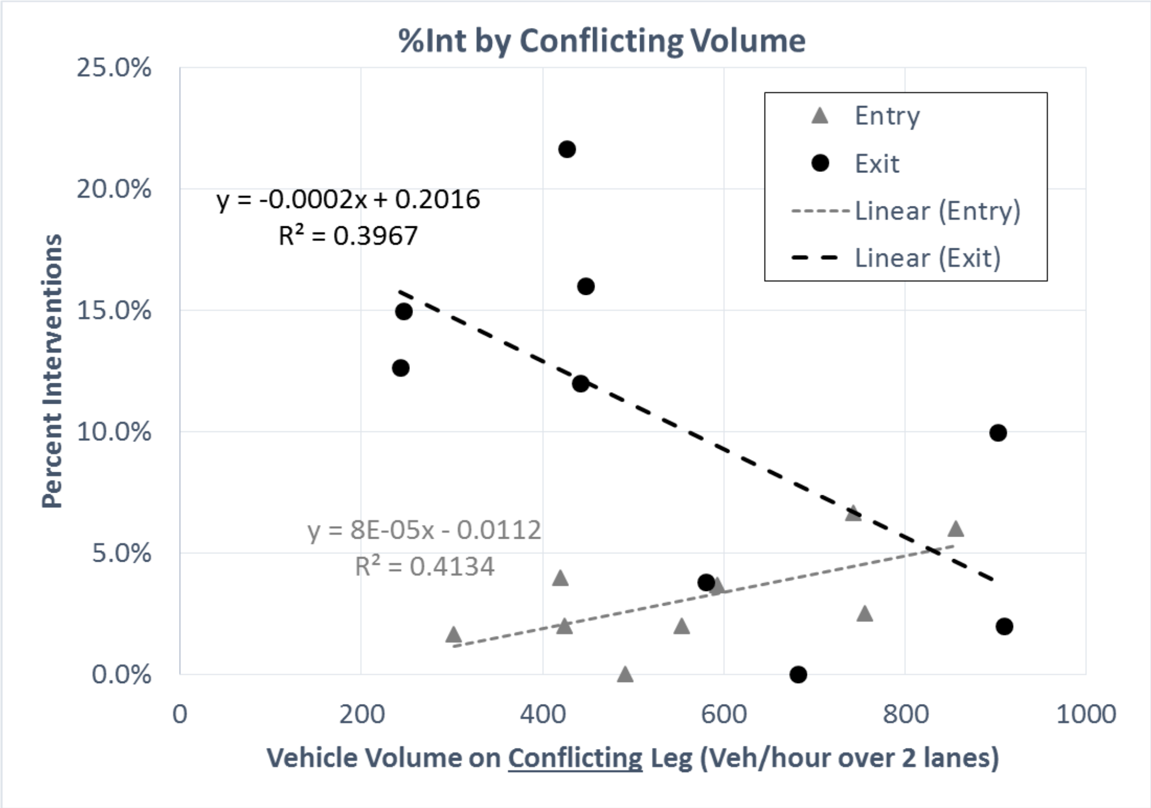

Figure 12. Graph. Percent intervention as a function of vehicle volume on conflicting leg.

Figure 12 suggests an increasing percent intervention rate with increasing vehicle volume at the crosswalk for the entry legs. With more traffic, there is a higher percent intervention rate at the entry. This is somewhat counterintuitive, as we would have expected there to be more yields with higher traffic volume, therefore reducing percent intervention. A positive slope of 0.00008 should be interpreted as a 0.8 percent increase in the intervention rate for each 100 additional vehicles.

There are three possible explanations for this trend. The first is that the trend may have to do with a vehicle moving in the second lane when the first lane is backed up, resulting in an increased potential for multiple-threat events with increasing traffic volume. Second, the trend may also have to do with drivers moving forward in a queue without noticing pedestrians and/or stopping on the crosswalk. Several interventions occurred when a previously stopped vehicle started to move again right when the pedestrian indicated they would cross. Those vehicles may have stopped because of the traffic queue, rather than actively yielding to the pedestrian. Third, a queued vehicle may have been stopped on top of the crosswalk, but was not perceived by the pedestrian.

The graphs in figure 12 suggest a decreasing percent intervention rate with increasing traffic volume for exit legs. This is also somewhat counterintuitive, as one might expect exits to have higher percent interventions with higher traffic volume. A negative slope of −0.0002 should be interpreted as a 2 percent decrease in percent interventions for each 100 additional vehicles.

One possible explanation here is that pedestrians faced with more traffic at exits had to wait for a gap or yield, and therefore made safer decisions. When exiting traffic is high, there could be a lot of auditory information conveyed to pedestrians that a crossing is NOT safe. However, when traffic is lighter, pedestrians may have perceived more gaps and attempted to cross during a quiet period with lighter volume, but missed an oncoming vehicle. At several sites, the team noted interventions because pedestrians did not perceive fast-moving cars exiting the circulating lane until very late.

Effect of RRFB Activation

The RRFB was always activated in trials measuring percent intervention. However, at nine approaches, the team performed the naturalistic yielding study both with and without the RRFB devices activated to compare yielding behavior between those conditions. The results are shown in figure 13.

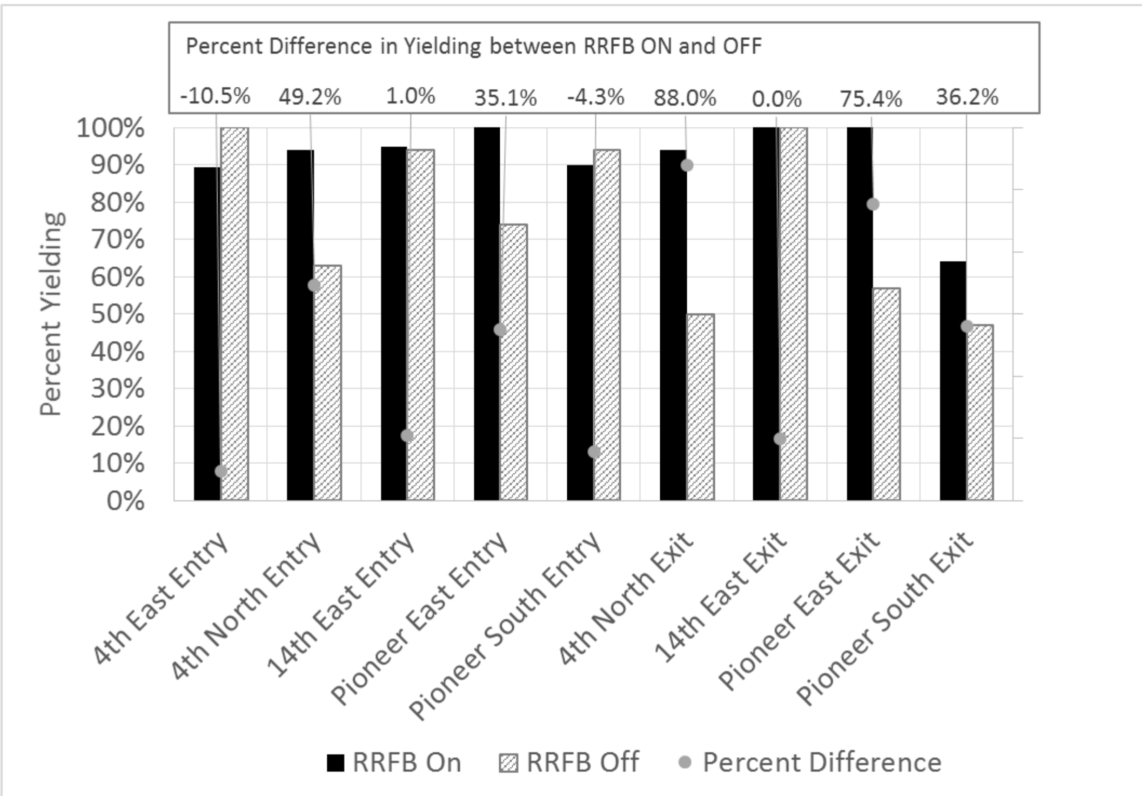

Figure 13. Chart. Effect of RRFB activation on yielding.

At five of the nine approaches, yielding was greater when the RRFB devices were activated than when they were not. When the RRFB was not activated at these five sites, yielding rates were all under 80 percent, but rose between 36 percent and 88 percent higher when the RRFB was activated. For the other four approaches, there was no major difference in yielding as a result of the RRFB activation. At these four sites, the yielding rate without the RRFB activates was already very high at above 90 percent, suggesting a driver culture generally very courteous towards pedestrians. This suggests that at the studied sites, the RRFB had more of an impact on yielding rates when those rates were 80 percent or lower with the RRFB off. Note that no sites where yield rates were compared between RRFB conditions had yielding rates below 45 percent, so these results should not be extrapolated to sites with lower non-RRFB yielding rates.

RRFB Design Details

In the geometry audits, the team noted some differences in where the RRFBs were installed and programmed at the studied sites. Some sites had RRFBs installed on the curbside and on the splitter island, while some only had the RRFBs on the curbside. Also, some RRFBs were configured to flash toward both entry and exit legs when activated by a single button, while others used two separately activated stages for crossing the entry and exit legs. The location of the push buttons and RRFBs varied between sites and for different approaches of the same site. Sometimes the RRFBs were between 1.5 to 7.6 m (5 to 25 ft) upstream of the crosswalk, and others were 1.5 to 3.0 m (5 to 10 ft) downstream of the crosswalk. There were also differences in how well the RRFBs were aimed toward oncoming traffic, and in the RRFBs' visibility to oncoming drivers. The characteristics of the RRFBs are summarized in table 5.

Table 5. RRFB design details.

City	Studied Leg	Exit/ Entry	No. of Lanes	Location	Pattern	LED Count	Audible Device	Locator Tone
Carmel, IN	Clay Terrace Blvd. North	Entry	Two	Curb and Island	Single-Stage	Low	No	No
Carmel, IN	Clay Terrace Blvd. North	Exit	Two	Curb and Island	Single-Stage	Low	No	No
Albany, NY	Fuller Rd. South	Entry	Two	Curbside Only	Single-Stage	High	No	No
Albany, NY	Fuller Rd. South	Exit	Two	Curbside Only	Single-Stage	High	No	No
Albany, NY	Fuller North	Entry	One (CTL)	Curbside Only	Single-Stage	High	No	No
Albany, NY	Fuller North	Exit	Two	Curbside Only	Single-Stage	High	No	No
Springfield, OR	Hayden Bridge Rd. East	Entry	Two	Curb and Island	Two-Stage	High	Yes	No
Springfield, OR	Hayden Bridge Rd. East	Exit	Two	Curb and Island	Two-Stage	High	Yes	No
Springfield, OR	Pioneer Pkwy. South	Entry	Two	Curb and Island	Two-Stage	High	Yes	No
Springfield, OR	Pioneer Pkwy. South	Exit	Two	Curb and Island	Two-Stage	High	Yes	No
Olympia, WA	Olympic St. North	Entry	Two	Curbside Only	Single-Stage	High	No	No
Olympia, WA	Olympic St. North	Exit	Two	Curbside Only	Single-Stage	High	No	No
Olympia, WA	4th Ave. East	Entry	Two	Curbside Only	Single-Stage	High	No	No
Olympia, WA	4th Ave. East	Exit	One	Curbside Only	Single-Stage	High	No	No
Olympia, WA	14th Ave. East	Entry	Two	Curbside Only	Single-Stage	High	No	No
Olympia, WA	14th Ave. East	Exit	Two	Curbside Only	Single-Stage	High	No	No
Oshkosh, WI	Jackson St. South	Entry	Two	Curb and Island	Two-Stage	High	Yes	No
Oshkosh, WI	Jackson St. South	Exit	Two	Curb and Island	Two-Stage	High	Yes	No
Oshkosh, WI	Murdock Ave. East	Entry	Two	Curb and Island	Two-Stage	High	Yes	No
Oshkosh, WI	Murdock Ave. East	Exit	Two	Curb and Island	Two-Stage	High	Yes	No
Davidson, NC	Griffith St. West	Entry	Two	Curb and Island	Two-Stage	High	Yes	Yes
Davidson, NC	Griffith St. West	Exit	Two	Curb and Island	Two-Stage	High	Yes	Yes
Davidson, NC	Griffith St. East	Entry	Two	Curb and Island	Two-Stage	High	Yes	Yes
Davidson, NC	Griffith St. East	Exit	Two	Curb and Island	Two-Stage	High	Yes	Yes

Team members observed that, in locations with an RRFB only on the curbside and not on the splitter island, there seemed to be more instances of drivers in the lane farthest away from curb failing to see the pedestrian or yield, particularly if traffic was backed up in the lane nearest the curb. Those drivers could be looking left for a gap in roundabout traffic and unaware of the pedestrian attempting to cross from the curb. Team members speculated that an RRFB on the island might make those drivers more aware of a pedestrian crossing on their right.

All RRFBs had push buttons for pedestrians to activate them, but only three locations had audible devices, and only one of those had devices with both a push button locator tone, to help blind travelers find the button, and a speech indication when the RRFBs were active. During data collection, the team noted that the speech messages varied between devices, confusing some pedestrians who were blind. For example, at one location the message was “Cross with caution, vehicles may not stop.” Some blind participants assumed that the message meant vehicles had a red light and that they should cross, indicating a lack of understanding of how RRFBs functioned; RRFBs had to be carefully explained to them. This confusion led to discussions between an FHWA MUTCD team and RRFB manufacturers, resulting in a recommendation that the message provide information only about what the device is doing. The current recommended message is “Yellow lights are flashing,” repeated twice.[(14)]

Blind participants also repeatedly stated that they had no way to know that an RRFB was present, or where it was, in the absence of a push button locator tone. If pedestrians do not look for or use the push button, and drivers expect them to do so, pedestrians could be at increased risk. Thus, both an audible push button locator tone and a speech message stating that “the yellow lights are flashing” are needed features for assuring that the RRFB is accessible to and usable by pedestrians who are blind.

Finally, the LEDs used in the devices varied from a “low” LED count (typically 2 rows of 4 for 8-LED arrays) to “high” LED count (typically 4 rows of 8 for 32-LED arrays). This may affect the perceived brightness of the display and the degree to which drivers notice it.

CHAPTER 4. DISCUSSION

OVERALL ASSESSMENT

The research team conducted a detailed accessibility audit at 12 two-lane approaches of 7 multilane roundabouts in Olympia, Washington; Springfield, Oregon; Carmel, Indiana; Oshkosh, Wisconsin; Davidson, North Carolina; and Albany, New York. The accessibility audit evaluated the accessibility performance of the roundabouts with RRFBs using five studies: a crossing indicator study, a naturalistic yielding study, a geometry audit, an exploratory speed study, and a 12-hour volume assessment. The goal was to characterize the accessibility of roundabouts with RRFBs based on driver behavior, pedestrian responses, environmental conditions, geometric design of the roundabout, and some macroscopic traffic characteristics such as volume and average speed.

The analysis of data trends and correlations between percent interventions, where a pedestrian who was blind would have crossed, but a COMS would have prevented the crossing because of a traffic threat, and other variables measured at the 12 roundabout approaches, point to some important overall observations:

- An increase in the degree of curvature (smaller radii and shorter curves) correlates with a decrease in percent interventions. This trend is true for both entries and exits, but with a stronger correlation for exit legs. Exit legs, on average, tend to have smaller degrees of curvature (larger radii) than entry legs, and are on average associated with greater percent interventions.

- An increase in the degree of curvature (smaller radii and shorter curves) also correlates with a decrease in the free-flow speed at the crosswalk. In addition, free-flow speeds were generally higher at exits than at entries. As curvature at entries and exits increase, free-flow speeds are expected to decrease, and the effect was about twice as strong at exits as at entries.

- A decrease in free-flow speed correlates with a decrease in the probability that drivers yield to pedestrians. With generally higher free-flow speeds at exits than entries, the associated probability of yielding is also lower at exits than at entries. The trends in this analysis were less strong than prior observations, but with each 1.6 km/h (1 mph) increase in free-flow speed, the entry and exit yield percentages are expected to decrease by 5.0 percent and 6.3 percent, respectively.

- An increase in the measured free-flow speed correlates with an increase in percent interventions. Free-flow speeds and interventions are generally higher at exits than entries, and a regression analysis suggests a 1.4 percent increase in interventions for each 1.6 km/h (1 mph) increase in free-flow speed at the exit. The R-squared value for this trend suggests that other factors also contribute to the rate of interventions, but the trend is nonetheless apparent. For the entry leg, the relationship is weaker with a suggested 0.4 percent increase in interventions for each 1.6 km/h (1.0 mph) increase in free-flow speed.

- An increase in the probability of yielding correlates with a reduction in percent interventions at the exit legs, with each 10 percent increase in yielding correlated with a reduction in percent interventions of 1.4 percent. No trend is evident for entry legs.

- An increase in traffic volume correlates with an increase in percent interventions at the entry legs, but with a decrease in percent interventions at the exit leg. With an R-squared value of approximately 0.40 for these trends, other factors beyond traffic volumes are expected to contribute to percent interventions. For the exit legs, the higher rate of interventions at low traffic volume is attributed to a “surprise effect,” where participants incorrectly identify a quiet period as a crossing opportunity, only to be surprised by a fast-moving vehicle accelerating around the circle toward the exit crosswalk. At higher volumes, the auditory information at the exit leg may be more reliable, reducing the number of decisions resulting in an intervention. For the entry lane, the increased rate of interventions with higher traffic volumes may be attributed to an increasing propensity for multiple threat events. In those cases, a yielding vehicle in the near lane inhibits the transfer of auditory and visual information between the pedestrian and a vehicle approaching in the far lane relative to the waiting pedestrian. This effect was particularly apparent at sites with imbalanced vehicle lane utilization that resulted in queuing in one lane while leaving the second (far) lane empty.

A closer study of the percent interventions suggest that a threshold may exist at an entry and exit radius of around 91.4 m (300 ft). At entry crosswalks, where all approaches had a radius of less than 91.4 m (300 ft), all percent interventions were less than 10 percent, and 9 out of 11 approaches were less than 5 percent intervention. This finding does not imply that all crosswalks with a controlling vehicle path radius of greater than 91.4 m (300 ft) are assured of being less accessible, nor that all crosswalks with a controlling vehicle path radius of less than 91.4 m (300 ft) are assured of being more accessible.

A threshold is also evident in the relationship between vehicular free-flow speed and percent intervention. The observed percent interventions changes noticeably at a vehicular free-flow speed of around 35 km/h (22 mph). For sites with free-flow speed below 35 km/h (22 mph), all but one location had less than 10 percent intervention, and 12 out of 14 had less than 5 percent intervention. For sites with free-flow speeds greater than 35 km/h (22 mph), five out of seven had more than 10 percent intervention, and six out of seven had more than 5 percent intervention. This finding does not imply that all crosswalks with free-flow vehicular speeds greater than 35 km/h (22 mph) are inaccessible, nor that all crosswalks with free-flow speeds less than this value are accessible.

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

While none of the trends above should be interpreted as being a direct causal factor, the correlations paint a useful picture of the types of variables associated with increased percent interventions at the studied multilane roundabout approaches as shown in figure 14.

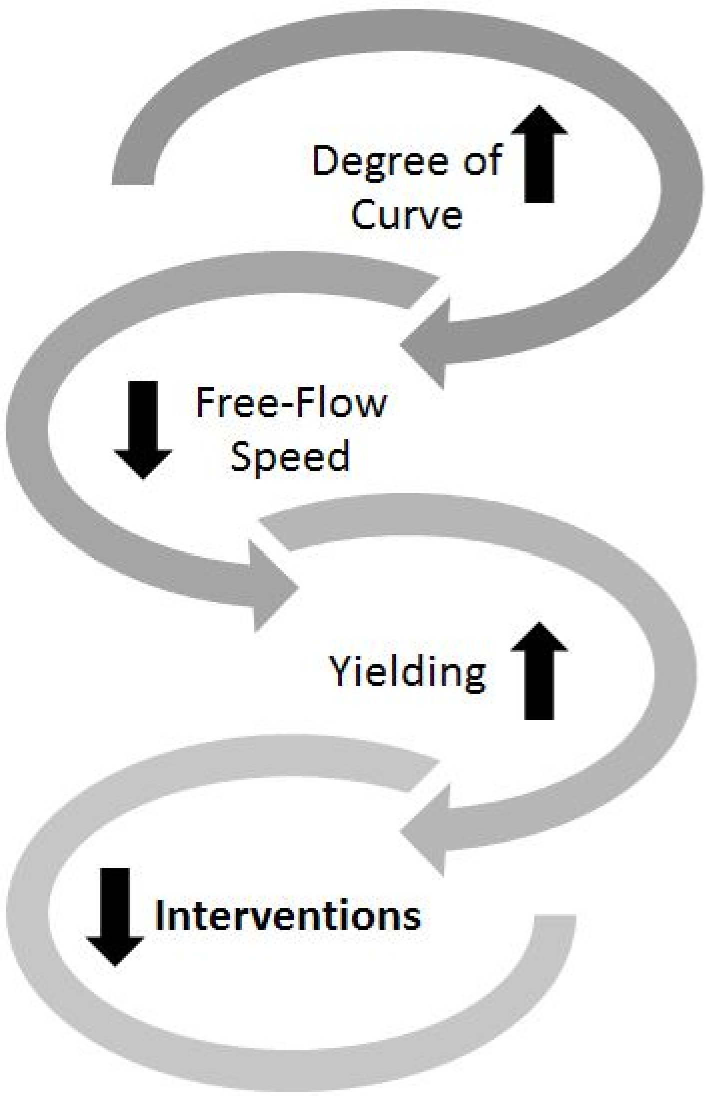

Figure 14. Diagram. Conceptual relationship between interventions and other factors.

Figure 14 illustrates conceptually that an increase in the degree of curvature (smaller radius), a reduction in free-flow speed, and an increase in yielding, are all associated with a reduction in percent intervention. The effect of traffic volumes is mixed, with higher traffic volumes being associated with a decrease in interventions at exit legs, but an increase for entry legs, likely due to an increased chance for multiple threat events with more vehicles. While the figure shows the relationship between degree of curve and interventions, other factors such as the ambient noise, visibility, lane utilization, and the local driver culture also appear to be important factors affecting percent interventions. As such, the relationships identified in this research document important and useful trends but are not a clear recipe for how to establish an accessible crossing environment at a multilane roundabout. Future research should thus build on these results as much as possible.

WAYFINDING

The team noted that some blind study participants were confused and had difficulty wayfinding and locating the crosswalk. This was true for example at the Olympic St. and 4th Ave. roundabout where the sidewalk was at the back of the curb, without landscaping separation. On the other hand, it appears that landscaping between the sidewalk and curb and other wayfinding features at the 14th and Jefferson roundabout (same participants, same town) made the participants more confident about finding crosswalks. Several sites had landscaping separating the sidewalk and curb, allowing blind participants to orient themselves and find the crosswalk more easily. Across the different sites, variations in sidewalk and roundabout design made it more difficult for blind participants to discern crosswalk location and alignment. This seemed to add to their concern over crossing decisions, leading some to say they would avoid the roundabout crossings if possible.

Several of the locations with RRFBs did not have audible signals or push button locator tones. Several participants pointed out that those are desirable features that help them use the device and to find the crosswalk. In addition, the location of the RRFBs in relation to the crosswalk varied, with some upstream of the crosswalk and others downstream. With audible messages, blind participants strongly preferred a downstream location, so the message was not repeating between the place where they were standing (within the crosswalk) and the traffic they needed to hear to make their crossing decision. Some commented that hearing the locator tone on the island assisted them in determining their line of travel toward the island.

While not an explicit component of the field protocol of the indicator study, these observations of the blind participants (and the COMS) point to the need for adequate landscaping, crosswalk location, push button location, push button locator tone, detectable warnings, and curb ramp alignment, which all contribute to the accessibility of a site from a wayfinding and usability perspective.

RRFB RECOMMENDATIONS

From the general RRFB observations, the team offers the following suggestions regarding placement, configuration, and type of the RRFB:

- RRFBs should preferably be installed as a *two-stage crossing* with separate devices for crosswalks on the roundabout’s entry and exit legs, each with its own push button, and push buttons on the splitter island. A two-stage configuration appears to more directly link flashers with pedestrian presence, and increases the probability that an RRFB is active when someone is crossing either lane. A two-stage configuration also reduces the need for excessively long flashing periods to cover a wide distribution of walking speeds, the effect of which is magnified with a one-stage crossing.

- For multilane approaches, RRFBs should be *installed on both ends of the crosswalk*, both at the curb and at the splitter island. Two RRFBs ensure that drivers in both entry or both exit lanes can see the device and whether or not it is activated. If there is only one RRFB on one side of the road, queued or yielding vehicles on that side of the road might block vehicles in the other lane from seeing the RRFB, resulting in a multiple-threat event.

- RRFBs should be installed to be as *visible* as possible to drivers, and the design should consider the brightness and orientation of the devices. This is especially critical at exit crossings to ensure RRBFs are visible to both circulating drivers and drivers turning right from the immediate upstream entry.

- RRFBs need to be outfitted with audible devices with both a push button locator tone and a speech message indicating when the yellow lights are flashing. A pedestrian who is blind will not otherwise be able to identify the presence or location of the device.

The audible device for the RRFB should be installed downstream of the crosswalk in the direction of traffic, so that (a) the pole does not block the line of sight between driver and pedestrian, and that (b) the audible message does not interfere with pedestrians' ability to hear approaching traffic.

INFLUENCE ON DESIGN PRACTICE

The findings from this study indicate that within the range of observed RRFB installations there are some likely relationships between traffic flow characteristics (volume and speed) and the availability of crossing opportunities in the form of gaps or yields. There is also some indication that the geometric configuration of a roundabout impacts its accessibility, either directly through obstruction of sight and hearing, or indirectly by allowing greater vehicular speeds. In particular, roundabouts with a low degree of curvature and deflection for vehicles at the exit leg tend to be associated with an increased rate of interventions even with RRFBs installed. From the data, it appears that such designs are less likely to be accessible than designs with a greater degree of curvature at exits. However, vehicle speed seems to mediate the effect of degree of curvature on percent intervention, and vehicle speeds can be likely controlled in other ways as needed.

These results need to be considered in the context of other factors that have been shown to have a strong impact on the accessibility of a site. These factors include ambient noise, pedestrian and crosswalk visibility, and vehicular lane utilization, and may have a greater influence in some cases than vehicular path radii and free-flow speeds. As such, sites with high ambient noise, poor visibility, and/or highly imbalanced lane utilization may prove to be inaccessible to blind pedestrians, even if vehicle speeds are low and the roundabout geometry features low radii.

The results of the present studies support the idea that RRFB-equipped multilane roundabouts can be accessible. The team postulates from experience with prior studies and publications, that an intervention rate of 3 percent or less is similar to the rate of interventions at single-lane roundabouts (for example in NCHRP Report 674[(3)]). Higher rates of intervention (above 5 percent) likely present a barrier for blind travelers crossing at these locations, with intervention rates above 10 percent representing a challenging and risky crossing environment. *It is emphasized here that these thresholds are not based on any formal guidance available, nor* *should they be used as the basis for policy and categorization of roundabouts*. The thresholds are merely introduced to help distinguish and categorize sites for the purpose of analysis and discussion.

The study results show that 10 of the 24 tested approaches had percent intervention rates of 3 percent or less, which includes entries and exits. Furthermore, in all cities, there were some blind participants who did not require any interventions, although that may have been related to time of day and large gaps in traffic. Four of the tested approaches (two entries and two exits) had zero interventions across all subjects. In addition to the 10 approaches with less than three percent interventions, four additional sites had intervention rates less than five percent.

Combined with findings of relatively low pedestrian crossing delay and high yielding rates, this supports the idea that multilane roundabout entries and exits with RRFBs can be accessible under some circumstances. From the results presented in this study, it appears that the RRFB is most likely to be an appropriate and sufficient treatment for roundabouts where the geometry supports a lower-speed environment and where there is an expectation of pedestrian activity. The effectiveness of the RRFB is likely also correlated with local driver culture, showing better performance in regions with generally high yielding compliance. For higher-speed roundabout designs, especially in areas with low pedestrian expectation and low yielding compliance, RRFBs alone are likely insufficient to establish accessibility. In such environments, three of the tested crosswalks had between five and 10 percent interventions. Furthermore, seven crosswalks had more than 10 percent interventions, and six of these were exit crosswalks (the seventh was a channelized bypass lane at an entry crosswalk). None of the observed entry crosswalks (excluding the crosswalk at a bypass lane) had over 10 percent interventions, and only two had over five percent intervention.

This study provides evidence that while RRFBs can be effective in providing accessible pedestrian crossings at multilane roundabouts there are limits to their effectiveness. Attributes influencing vehicle speed at crosswalks should be very carefully considered by the designer. A roundabout design that is more likely to result in higher vehicle speeds at the crosswalk is expected to result in lower yielding and increased pedestrian risk than a roundabout design ensuring lower vehicle speeds. Additional speed control treatments may help offset these effects, but no such treatments were evaluated in this research.

APPENDIX A. DATA COLLECTION PROTOCOL DETAILS

INDICATOR STUDY

The first portion of the audit involved the help of five to eight blind participants recruited for the study by the research team. Participants were individuals who were totally blind (no more than light perception), and who regularly crossed streets independently. One set of participants was used for both roundabouts in Olympia; after collecting data at one roundabout the team would drive to the second roundabout and complete the data collection at that location with the same subject. A set of five to eight different participants were recruited in each city.

Each participants signed the Institutional Review Board (IRB)-approved consent form, then were familiarized with the roundabout and the RRFB treatment before the study, and crossed the approaches with a Certified Orientation and Mobility Specialist (COMS) to get an estimate of the crossing width in order to determine crossable gaps. During the actual study, participants approached the crossing and indicated their decision about when they would cross without actually stepping into the street. The research approach has been previously applied to multilane roundabout studies in Oakland County, MI, and Nashville, TN.[1,15] The protocol is faster than a crossing study and, most importantly, does not require the participant to step into the street, thereby reducing risk of injury.

The study included 10 trials for each of the two approaches (one entry and one exit) at each studied leg. In each trial, participants walked with the COMS toward the crosswalk; as they approached, the COMS pushed the push button on the flashers and assisted the participant as necessary to align to cross. While approaching, participants were reminded which approach of the roundabout was in front of them. For example they were told, “These are the entry lanes, two lanes of traffic from your left. I’m pushing the button. Raise your hand when you would cross.” A trial was concluded by the participant’s indication that he/she would cross, or by timing-out after two minutes. At that time, the participant was asked to step back from the crosswalk and walk for a short distance along the sidewalk to allow for traffic to be cleared and then walk back to start a new trial. It should be noted that the COMS would sometimes ask the participant to go ahead and cross the street to “reward” very long yield times.

After each trial the COMS evaluated the safety of the crossing decisions by showing a hand signal to a computer operator to indicate if the crossing decision was an *estimated intervention,* a *risky decision,* or a *safe decision* in an actual crossing by a blind pedestrian. The computer operator also rated each crossing event as safe, risky, or as an estimated intervention, prior to receiving the COMS’s indication. These judgments were therefore independently made by the expert observer and the COMS. These two independent estimates of intervention were then compared later to assure that the COMS rating provided an accurate risk assessment of the crossing decision (see Appendix C). The “risky” events are not explicitly used in the analysis.

Indicator Study Data Collection Set-Up

The study combined two approaches for data collection: real-time coding done on a laptop computer in the field, and post-processing of data from video recordings and speed measurements in the office. The real-time coding was performed using a Visual Basic macro that records time stamps in a Microsoft Excel spreadsheet whenever the analyst (seated near the crosswalk while the indicator trials were conducted) pushed certain predefined keys. For example, in using this computer program to record pedestrian delay, the analyst would push a button when the COMS said “raise your hand when you would cross” and another key when the pedestrian indicated he or she would initiate the crossing. The analyst was able to hear the COMS’s instructions to participants through a wireless microphone.

During the trials, a ground-level camera was positioned at the approach crosswalk to record participant and vehicle movements, as well as recording the speed from the screen. The camera also recorded the COMS’s instructions and the participant’s responses from a wireless microphone used by the COMS. Additionally, a tripod-mounted sound measurement device was positioned near the crosswalk for the Olympia, WA, and Springfield, OR, sites, which recorded ambient sound levels during each trial that are later linked to pedestrian decision making. The sound measurement device was not used for subsequent studies.

Indicator Study Performance Measures

Measures of participant behavior and measurement of driver behavior were obtained during this study. Participant measures included participant delay and safety, yield utilization rate, and gap utilization rates, and are listed in table 6. Vehicle measures include driver yielding rate and are listed in table 7.

Table 6. Indicator study participant measures.

Measure	Description/Definition
Participant Delay	The time in seconds from the start of the trial ("raise your hand when you would cross") to the moment that the participants indicated they would cross by raising their hand.
Participant Supplemental Delay	The time in seconds of the first "crossing opportunity" (in a form of crossable gap or yield that was either utilized or not by the participant) to the moment that participants indicated they would cross.
Estimated Interventions	The frequency of events in which COMS decided the crossing decision made the participant that would have resulted in a dangerous crossing and the COMS intervening, and indicated so to the experimenter observer.
Observer Estimated Interventions	The frequency of events in which the experimenter observer noted a decision made by participant that would have resulted in an intervention in a crossing experiment.
Yield Utilization Rate	The percentage of vehicle yields that was detected and utilized by participants by indicating they would have crossed.
Crossable-gap Utilization Rate	The percentage of "crossable-gaps" that were utilized by participants by indicating they would have crossed.
Latency	Pedestrian latency in detecting gap or yield as a crossing opportunity, defined as the time in seconds between when the crossing opportunity presented itself (gap "opens" or driver yields) and the time when the participants raised their hand.

Table 7. Indicator study vehicle measures.

Measure	Description/Definition
Yield Rate	The percentage of vehicles yielding during a trial (yielding vehicles to total vehicles).
Crossable Gap Rate	The percentage of crossable gaps (crossable gaps to total gaps).
Driver Compliance	The percentage of drivers yielding and not yielding, relative to the active state of the RRFB device (yielding vehicles to total vehicles with RRFB active).
Driver Patience	Average duration in seconds that a driver was stopped when waiting for the pedestrian to make a crossing decision.

NATURALISTIC YIELDING STUDY

The purpose of the study was to understand driver yielding behavior and conditions affecting the probability of driver yielding. This study was conducted by a member of the research team approaching the crosswalk at random intervals while an analyst recorded the drivers' yield responses (yes/no), as well as a variety of attributes of the interaction between pedestrian and driver. These attributes or explanatory variables include crossing leg (entry/exit), lane position (near/far), platooning (yes/no), vehicle type (light/heavy), presence of downstream conflict at the entry approach, through or right turning vehicles at the exit, presence of multiple pedestrians, if the vehicle was already stopped, presence of yield in the adjacent lane, speed of the vehicle, and if the pedestrian crossed in a yield or gap. A video camera and a synchronized radar speed measurement system were used to measure and record approaching vehicle speed. A trial started as the pedestrian approached the crosswalk and took one step "into" the crosswalk and stopped and waited for a vehicle to yield. The study goal was to complete 20 trials per location for each of four different conditions: blind (carrying a white cane and wearing sunglasses, simulating the appearance of a blind individual), sighted, with RRFB on, and with RRFB off. Each condition was further tested at crosswalks at roundabout entry and exit legs, which brought the total sample size at each studied approach to 160 crossings. In some cases, the study had to be cut short due to time constraints.

SPEED STUDY

In order to get more insight into the relationship between the geometric parameters of the roundabout and actual free flow speed of the vehicles at the crosswalk, a sample of 30 free-flow speeds was collected at each studied crosswalk on the entry and exit leg. The speeds were collected with a radar speed gun at the time that a vehicle approached the crosswalk with free-flow speed, i.e. no platooning or no pedestrians were present. For the entry and exit speed measurements the researchers stood 6.1 m (20 ft) downstream of the crosswalk in the respective leg and positioned the speed gun to get a close-to-direct line of sight at the upcoming vehicle, while attempting to mask the speed gun from drivers. Since the prior audit components (yield study and indicator study) did not control for free-flow conditions, this speed study was geared at isolating geometric effects from driver culture at each studied approach.

GEOMETRY AUDIT

A team of trained observers documented critical geometric features of the roundabout including inscribed diameter, roundabout design radii, crosswalk location relative to the circulating lane, the presence and orientation of truncated dome detectable warnings, landscaping, wayfinding features, and other factors. The documentation was a detailed and narrated photo diary of the sites, with special emphasis on features that, according to prior research, impact accessibility.

12-HOUR VOLUME ASSESSMENT

The team deployed overhead video equipment at each studied crosswalk, and recorded a total of 12 hours of data. In post-processing in the office, these video records were used to (1) extract vehicular volume time stamps for entering, exiting, and circulating lanes, and (2) evaluate gap distributions across a full day of analysis. While indicator and yielding studies occurred at only select time periods throughout the day, the 12-hour volume assessment was intended to allow the team to extrapolate results to other times of day. The volume count was combined with a time-stamped collection of vehicle events at the crosswalk, which can be used to develop a (crossable) gap distribution at the entry and exit leg across a 12-hour day.

APPENDIX B. SITE DETAILS

The study protocol presented here was conducted at 12 two-lane approaches of seven multilane roundabouts:

1. Olympic St. W and 4th Ave. W, Olympia, WA;
2. Jefferson St. SE and 14th Ave. SE, Olympia, WA;
3. Pioneer Pkwy. and Hayden Bridge Rd., Springfield, OR;
4. Clay Terrace Blvd., Carmel, IN;
5. Fuller Road at Washington Ave., Albany, NY;
6. Jackson St. at Murdock Ave, Oshkosh, WI; and
7. Griffith Street at Harbor Place, Davidson, NC.

This appendix presents aerial views of these locations, and summarizes key observations and points of interest by site for the seven studied roundabouts. These observations are intended to supplement the observations and performance measures described above, with an emphasis on more qualitative observations.

Olympic St. W and 4th Ave. W, Olympia, WA

Figure 15 shows the Google aerial view of the roundabout located at the intersection of Olympic St. W and 4th Ave. W in the city of Olympia, WA. The audit was applied to the east leg on 4th Ave. W and north leg on Olympic St. W, both entry and exit. Figure 16 and figure 17 show the ground level view of the studied approaches. All the approaches have two lanes, except for the 4th Ave. exit, which is a single lane.

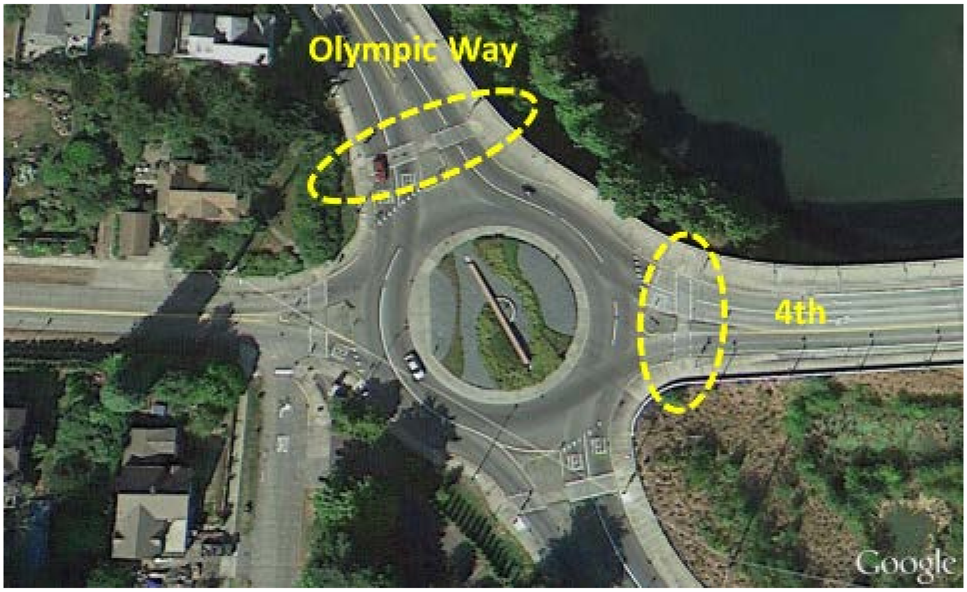

Figure 15. Photo. Aerial view of Olympic St. W at 4th Ave. W, Olympia WA.

Figure 16. Photo. 4th Ave. W, east leg two-lane entry, one-lane exit, Olympia WA.

Figure 17. Photo. Olympic St. W, north leg two-lane Entry, two-lane exit, Olympia WA.

This site exhibited high pedestrian and bicycle activity, and thus high driver expectation of pedestrians. Olympia, WA, generally had a very compliant driver culture with drivers expecting to yield and expecting pedestrians to activate the RRFB. At this roundabout, a steep approach grade at Olympic St. (northern approach) resulted in higher entering speeds (downhill) and lower exiting speeds, which were reflected in the safety performance at these two legs. The east exit on 4th was a single-lane exit, and showed lower interventions and delay than most two-lane exits studied in this research.

The RRFB installation only used the treatment on the curbside, and no RRFBs were installed on the splitter island. This lack of treatment and driver information on the inside approach lane may have contributed to the relatively high rate of interventions on the east entry leg, which were almost all attributed to multiple threat events. A second RRFB (per approach) on the splitter island may have provided the necessary additional information to drivers at this high yield compliance site, and allowed them to identify a stopped outside-lane vehicle as a vehicle yielding to pedestrians as opposed to one waiting to enter the circle.

Jefferson St. SE and 14th Ave. SE, Olympia, WA

Figure 18 shows a view of the second studied roundabout in Olympia, WA. This roundabout is located at the intersection of Jefferson St. SE and 14th Ave. SE. Only one approach was evaluated for the indicator study, which is shown in a street-level view in figure 19. The exit leg of 14th Ave. SE, westbound was also studied in the naturalistic yielding study (front crosswalk in figure 19). The studied east leg of 14th Ave. SE has two entering and two exiting lanes, and experiences heavy inbound a.m. peak volumes from I-5 as shown by a long queue in the right approach lane in figure 19. A close-up view of the studied entry leg is shown in figure 20.

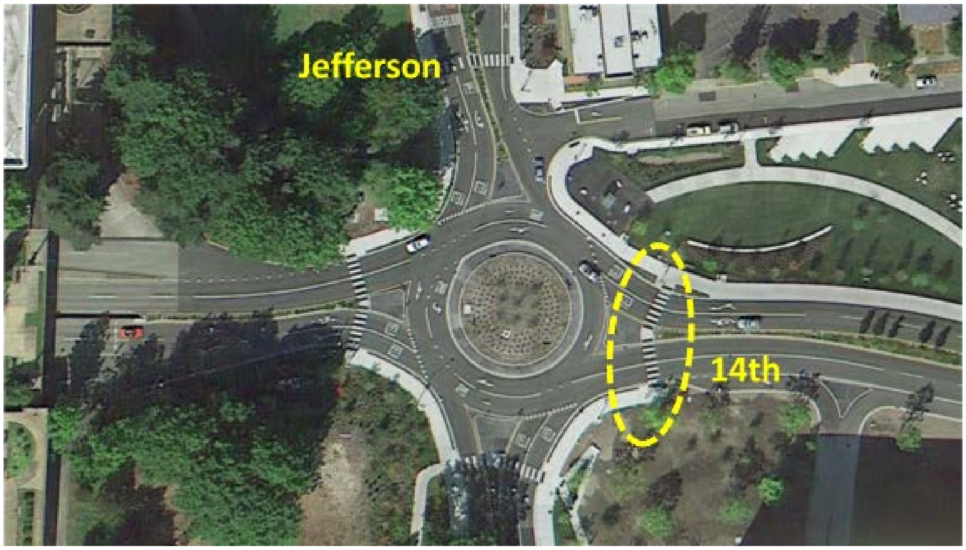

Figure 18. Photo. Aerial view of 14th and Jefferson roundabout in Olympia, WA.


Figure 19: Photo. Phase I data collection site, Jefferson St. at 14th Ave. SE, Olympia WA.


Figure 20. Photo. 14th Ave SE, east leg two-lane entry, two-lane exit, Olympia WA.

This site generally exhibited high pedestrian and bicycle activity, and thus high driver expectation of pedestrians. Similar to the other Olympia, WA, site, this location showed a very compliant driver culture with drivers expecting to yield and expecting pedestrians to activate the RRFB. There was further high police presence adjacent to state government complex.

The site had an elevated rate of entry-leg interventions, which may be explained by a combination of high volumes, pedestrian expectation, and sound levels. The east approach to the roundabout exhibited highly imbalanced lane utilization of traffic coming off the interstate, which was especially prevalent in the a.m. peak period. Drivers tended to heavily favor the right approach lane (closest to pedestrians crossing from curb at the entry leg), which resulted in several multiple threat events with fast-moving cars approaching in the left approach lane. Similar to the other Olympia, WA, site, no RRFB was installed on the splitter island. If present, this second RRFB device may have provided drivers in the left approach lane with additional information that a pedestrian was about to cross.

Pioneer Pkwy. and Hayden Bridge Rd., Springfield, OR

Figure 21 shows the Google aerial view of the roundabout located at the intersection of Pioneer Pkwy. and Hayden Bridge Rd. in the city of Springfield, OR. The team studied the south leg on Pioneer Pkwy. and east leg on Hayden Bridge Rd. for this phase of data collection. Both approaches featured two-lane entries and exits. Ground-level pictures of the studied approaches are shown in figure 22 and figure 23.

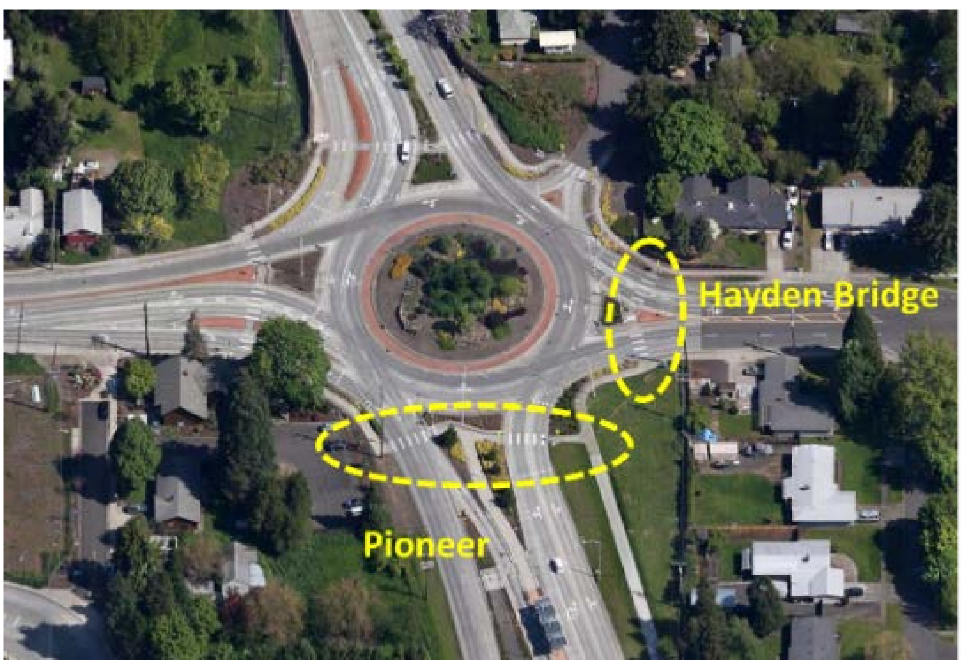

Figure 21. Photo. Aerial view of Pioneer Pkwy. and Hayden Bridge Rd., Springfield, OR.

Figure 22. Photo. Pioneer Pkwy. south leg two-lane entry, two-lane exit, Springfield, OR.

Figure 23. Photo. Hayden Bridge Rd. east leg two-lane entry, two-lane exit, Springfield, OR.

This roundabout design has a larger roundabout diameter and entry/exit radii than the previously described sites in Olympia, WA. A bus rapid transit station on the south approach results in high pedestrian volume and driver expectation of pedestrians. The roundabout was very busy during certain times of day with both vehicles and pedestrians.

The site had a high rate of exit-leg interventions at the south exit, which featured an upstream channelized right-turn lane to accommodate the eastbound to southbound right-turning movement. The team noted that a fairly large portion of interventions seemed to have been associated with right-turning vehicles from the west approach. Being faced with heavy conflicting flows, it appears that those upstream right-turn drivers would accelerate rapidly into the few available gaps in the circulating lane, with drivers' heads rotated to the left towards the conflicting traffic stream. The Pioneer Pkwy. exit-leg crosswalk is located relatively close to the circulating lane, and driver reaction time at that exit leg is very short because they accelerate rapidly and are facing away from the crosswalk. This may at least partially explain the low yielding rate observed at the south exit. In addition, the rapid acceleration from a stopped position within a short distance also appeared to make it very difficult for blind participants to react to these vehicles. The roundabout geometry and landscaping appeared to contribute to some sight obstruction between the right-turning driver and the waiting pedestrian.

The Hayden Bridge exit leg did not have the same upstream channelized right-turn lane, but still had enough interventions to indicate that blind participants would be challenged there.

Jackson St. at Murdock Ave, Oshkosh, WI

Figure 24 shows the Google aerial view of the roundabout located at the intersection of Jackson St. and Murdock Ave. in the city of Oshkosh, WI. The audit was applied to the east leg Murdock Ave. and south leg on Jackson St., both entry and exit. Figure 25 shows a street-level view of the southern approach on Jackson St.

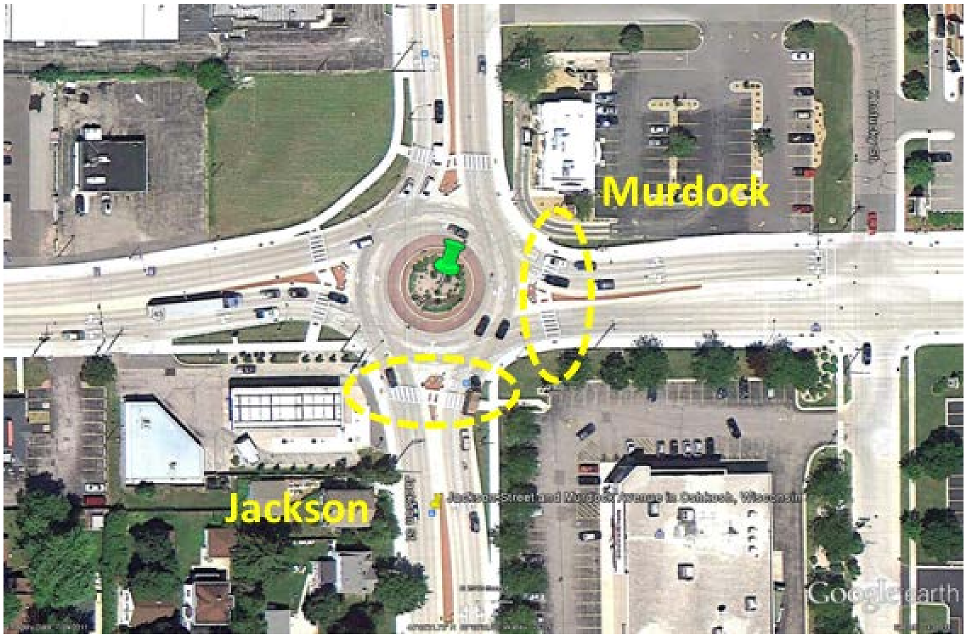

Figure 24. Photo. Aerial view of Jackson St. and Murdock Ave., Oshkosh, WI.

Figure 25. Photo. Street-level view of Southern Approach on Jackson Street., Oshkosh, WI.

This site was busy with traffic from all approaches with varying patterns throughout the day. The roundabout featured moderate to heavy pedestrian activity throughout the day, including children, elderly pedestrians, and some wheelchair users. The roundabout design is offset left with relatively low deflection at exit. Observations by the team suggested that drivers seemed impatient, with horn-blowing at pedestrians or other drivers yielding to pedestrians. One exit crosswalk (south exit) was very close to the circulating roadway due to a gas station exit driveway, resulting in poor visibility of the crosswalk for circulating drivers. However, both exit crosswalks were problematic for blind pedestrians.

Clay Terrace Blvd, Carmel, IN

Figure 26 shows an aerial photo of the data collection site located in Carmel, IN, in the Clay Terrace shopping center. Only the north east approach of the roundabout was equipped with RRFB and therefore that approach was the only one studied. Figure 27 and figure 28 show street-level views of the studied crosswalk and approach to the roundabout.

Figure 26. Photo. Phase II data collection site, Clay Terrace Blvd., Carmel, IN.

Figure 27. Photo. Street-level view of the studied crosswalk on Clay Terrace Blvd., Carmel, IN.

Figure 28. Photo. Street-level view of approach on Clay Terrace Blvd., Carmel, IN.

This roundabout was located on a public street in a shopping center environment with high pedestrian expectation, including a significant amount of parents with children and strollers. There are two roundabouts on Clay Terrace Blvd., and the study focused on one crosswalk at the northern site, the only location were RRFBs were installed. The roundabout had signs on the splitter islands (which are not accessible to blind pedestrians) informing pedestrians to yield to vehicles. The roundabout featured relatively low speeds. Upstream signals seemed to result in platoons of traffic at the roundabout entries and exits.

Fuller Road at Washington Ave., Albany, NY

Figure 29 shows an aerial photo of the data collection site in Albany, NY, at the intersection of Fuller Rd. and Washington Ave. Figure 30 and figure 31 show street-level views of the studied crosswalks on the southern and northern approaches to the roundabout, respectively. The picture of the northern approach shows the channelized turn lane that was evaluated at the entry leg.

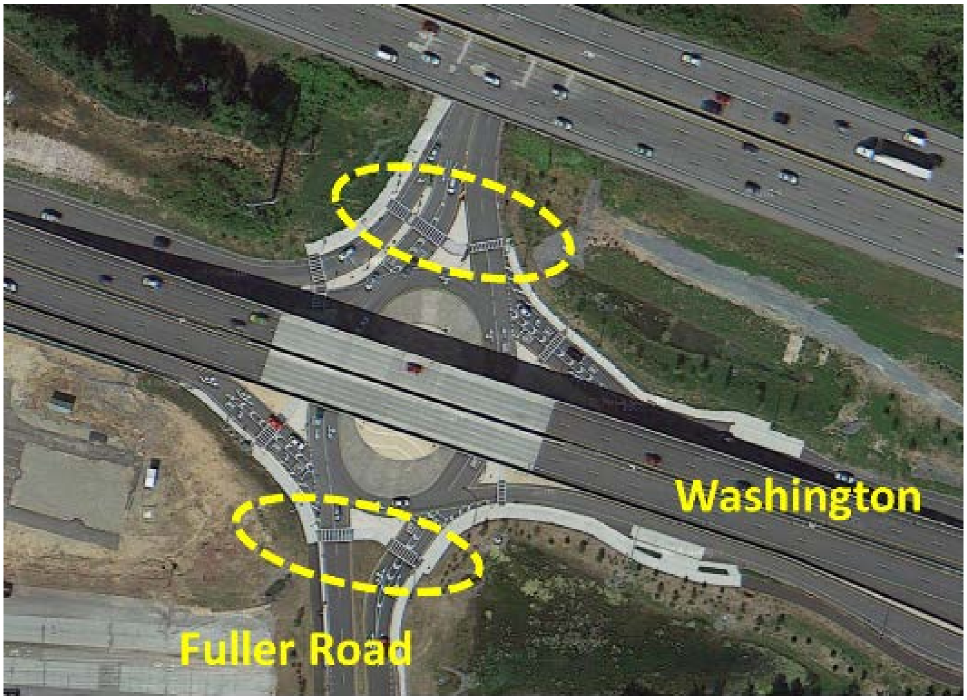

Figure 29. Photo. Aerial view of Fuller Rd. and Washington Ave. roundabout in Albany, NY.

Figure 30. Photo. Street-level view of southern approach on Fuller Rd., Albany, NY.

Figure 31. Photo. Street-level view of channelized turn lane on northern approach on Fuller Rd., Albany, NY.

This roundabout was an underpass at an expressway, resulting in unique sound patterns with bridge abutments masking audible information and causing echoes. As such, it was very difficult to see or hear vehicles coming around the circle towards the exit, with drivers traveling very fast when there was low traffic volume. The roundabout design featured a very strong offset left design with very little deflection at exit.

The northern entry data collection was at a channelized turn lane flowing onto an expressway. There were crosswalks at two locations on that turn lane, but only the upstream location (typical entry crossing) was studied. At both the north and south crossings, some of the traffic in the exit lane was just exiting the expressway ramp and making right turns toward the crosswalk; there may have also been limited reaction time for drivers at these sites, similar to the situation at Pioneer Pkwy. and Hayden Bridge Rd. in Oregon. The site was near a college campus and trail system, but with generally very little pedestrian activity, and drivers did not seem to expect pedestrians there.

Griffith St. at Harbour Place, Davidson, NC

Figure 32 shows an aerial photo of the data collection site in Davidson, NC, at the intersection of Griffith St. and Harbour Place Dr. Figure 33 and figure 34 show street-level views of the studied crosswalk on the west approach to the roundabout. Figure 35 shows the studied east approach to the roundabout.

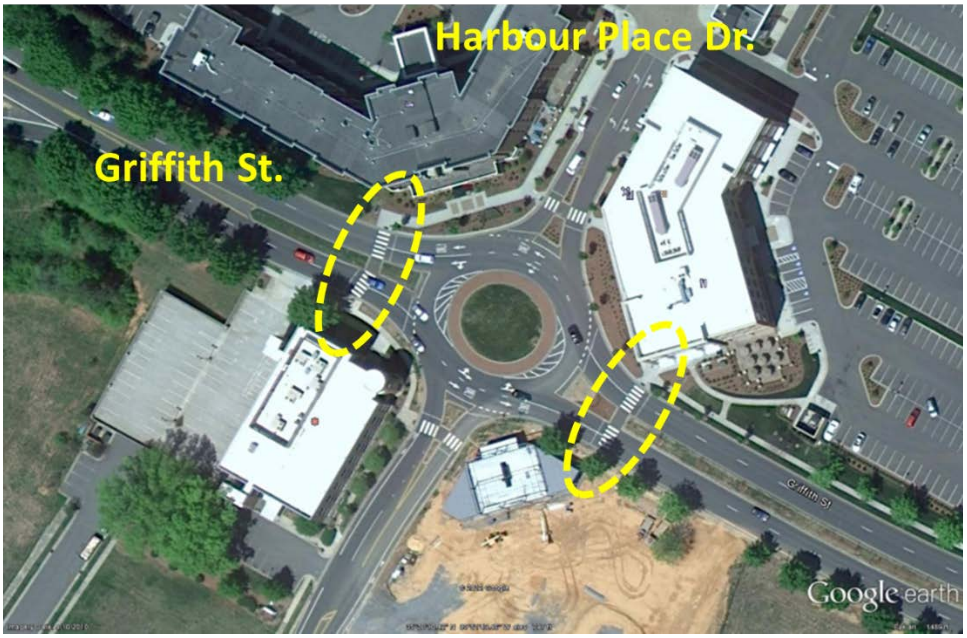

Figure 32. Photo. Aerial view of Griffith St. and Harbour Place Dr. in Davidson, NC.

Figure 33. Photo. Street-level view of west approach entry in Davidson, NC.

Figure 34. Photo. Crosswalk view at west approach in Davidson, NC.

Figure 35. Photo. Crosswalk view of east approach in Davidson, NC.

This site was located on the main arterial connecting Interstate I-77 to the town of Davidson, NC. The roundabout at Griffith St. and Harbour Place Dr. had steady flow in the east-west direction and through the studied crosswalks, but little traffic on the north and south legs with more development and concomitant changes in traffic expected in the future. The land surrounding the roundabout was built close to the street level, giving this site an overall urban feel with high expectation of pedestrians. The team noted a generally high level of driver courtesy in the town of Davidson, NC, but also noted differences in driver behavior for the two directions of travel. Drivers appeared to be more patient traveling west to east (from interstate into town) than in the opposite direction (towards the interchange). There also were some differences in sight distance between the east and west approaches, related to trees, slopes, and other features near the roundabout.

APPENDIX C. SUPPLEMENTAL ANALYSIS DETAILS

This appendix contains supplemental data analysis results for the 12 studied roundabout approaches.

Percent Interventions by Traffic Volume by Subject

To further evaluate the effects of traffic volume, the volume vs. intervention analysis in the previous section was repeated using the individual subject-level data. This section evaluates percent interventions as a function of traffic volume on the conflicting lane, the lane closest to the participant attempting to cross. While volume on that lane is an important variable, other traffic in the roundabout could potentially mask the sound of traffic approaching in that lane. The graph in figure 36 distinguishes entry (gray triangles) and exit (black circles), and further show a linear trend line fit to the data. The single-lane exit and channelized turn lane trials were excluded from this analysis.

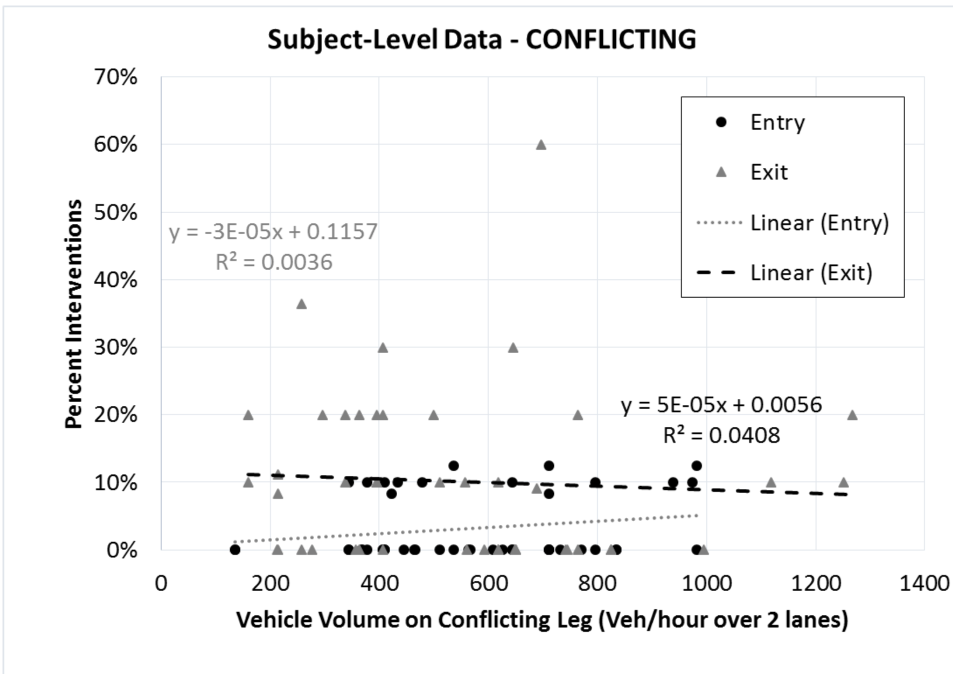

Figure 36. Graph. Percent intervention as a function of vehicle volume on conflicting leg at subject level.

Figure 36 shows no clear trends of the rate of interventions with higher traffic volumes for the entry or exit leg.

Percent Intervention by Volume-to-Capacity Ratio (v/c)

This section focuses on the entry leg and shows percent interventions as a function of volume-to-capacity ratio, or v/c. Figure 37 assumes the HCM 2010[16] capacity relationship for roundabouts with an intercept of 1,130 vehicles per hour per lane, and a slope parameter of 0.0001. The data are shown only for the roundabouts where conflicting circulating flow was available. Results are shown on a per-approach basis, with one data point corresponding to one approach, in figure 37, and on a per-subject basis, with one data point corresponding to one participant, figure 38.

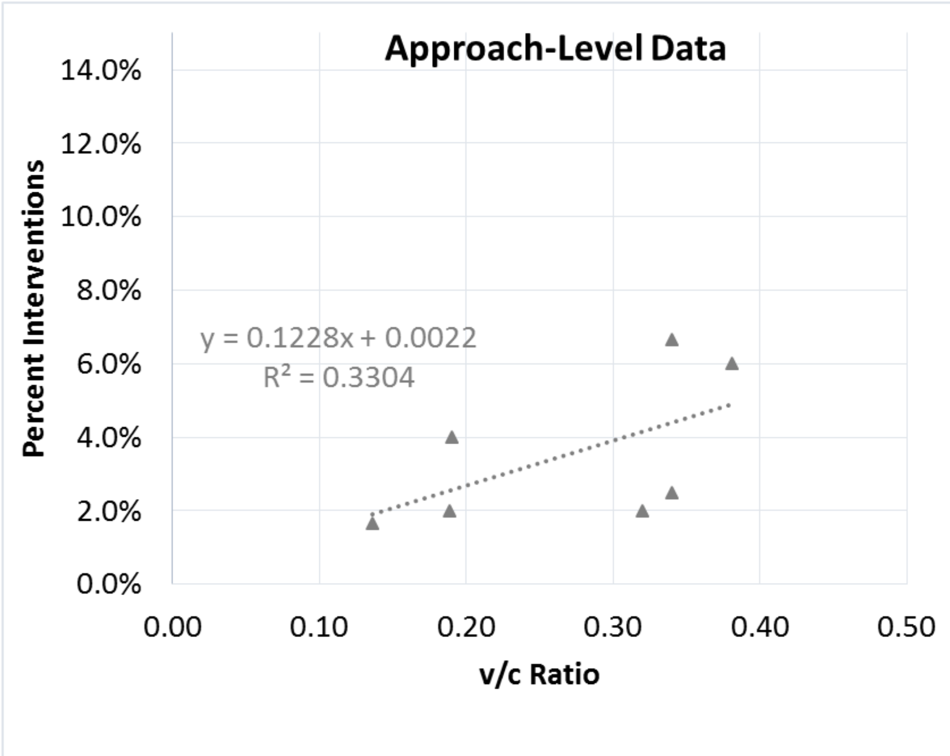

Figure 37. Graph. Percent intervention as a function of volume-to-capacity ratio at entry - approach level data.

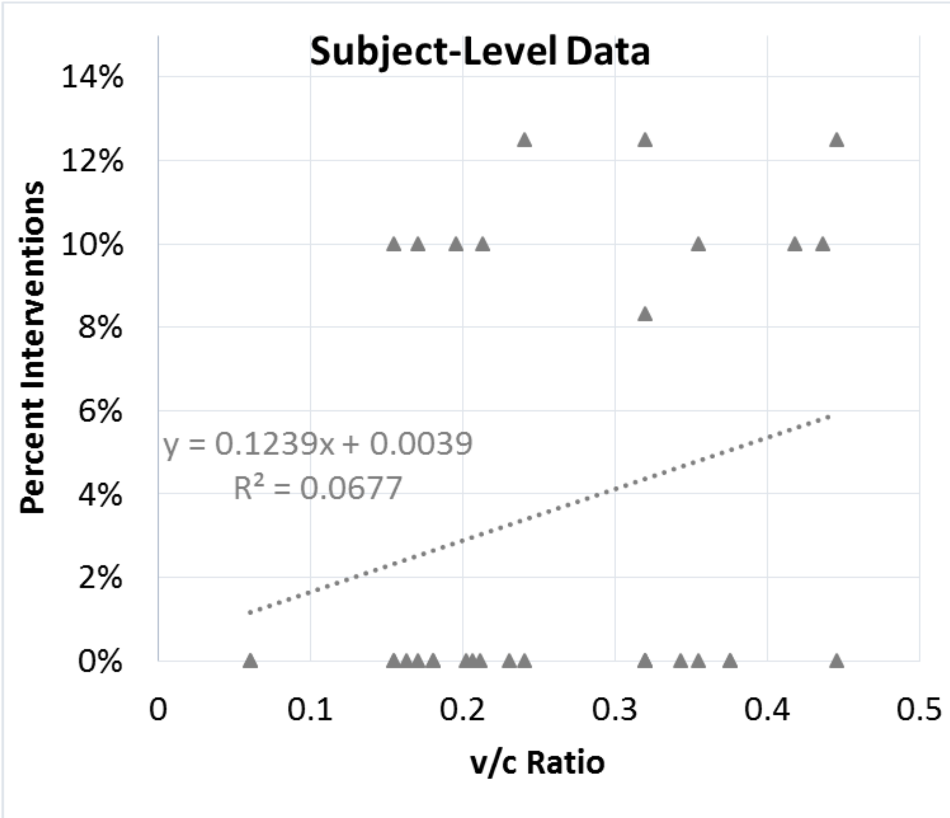

Figure 38. Graph. Percent intervention as a function of volume-to-capacity ratio at entry - subject level data.

Based on figure 37 and figure 38, the v/c analysis shows a similar upward trend in interventions with increasing traffic volumes. The trend is strong for approach level, but more scattered for subject-level data. The subject-level data have two distinct regimes: one for zero interventions, and one at about 10 percent.

Percent Interventions by Volume by Site

This section is an evaluation of percent interventions as a function of traffic volume on the lanes closest to the participant based on the individual subject-level data divided by site.

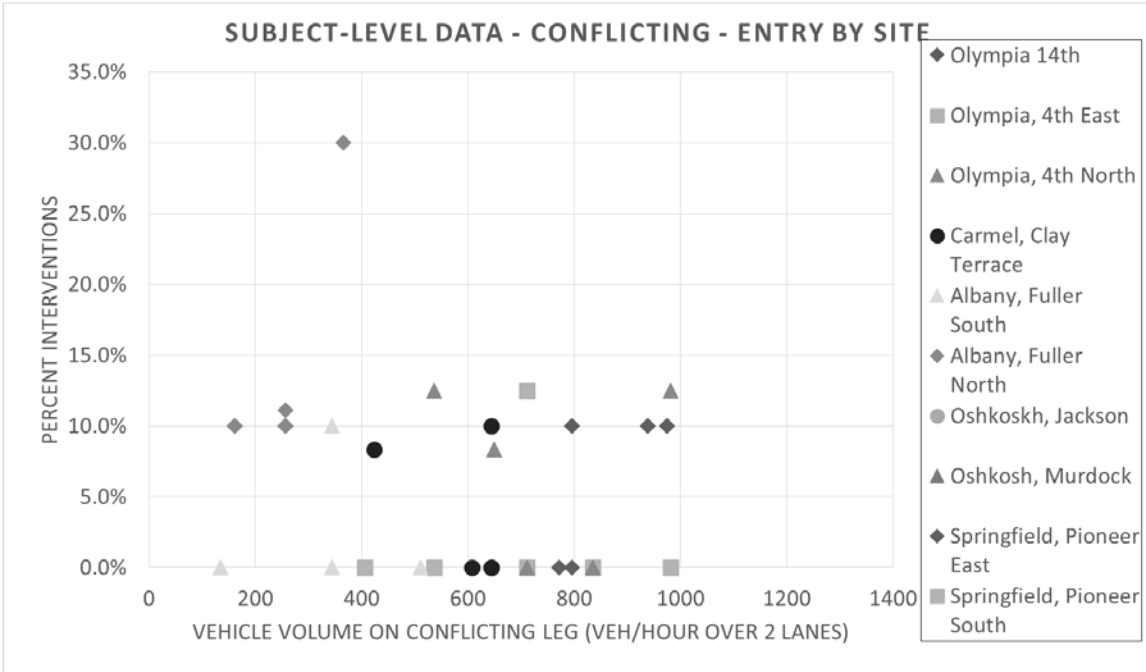

Figure 39. Plot. Percent intervention as a function of vehicle volume for individual sites- entry.

Figure 39 shows there are no clear patterns evident from the data. The following are the noteworthy observations for each site. 14th Ave. in Olympia, WA, generally had high volumes with a mix of interventions (0% to 10%). 4th St. East in Olympia, WA, had mid to high volume with generally zero interventions, except for one participant (13%). 4th St. North in Olympia, WA, had mid to high volumes with a mix of interventions (0% to12%). Clay Terrace Blvd. in Carmel, IN, had mid to low volumes with a mix of interventions (0% to 10%). South Fuller St. in Albany, NY, had mid to low volumes with a mix of interventions (0% to 10%). North Fuller St. in Albany, NY (channelized turn lane) had relatively low volumes with high interventions (10% to 30%). Jackson St. in Oshkosh, WI, had mid-level volumes with mostly zero interventions, except for one participant (10%). Murdock Ave. in Oshkosh, WI, had mid-level volumes with all zero interventions. Hayden Bridge Rd. East in Springfield, OR, has mid to low volumes with generally zero interventions, except for one participant (10%). Pioneer Pkwy. South in Springfield, OR, has mid to low volumes with a mix of interventions (0% to10%).

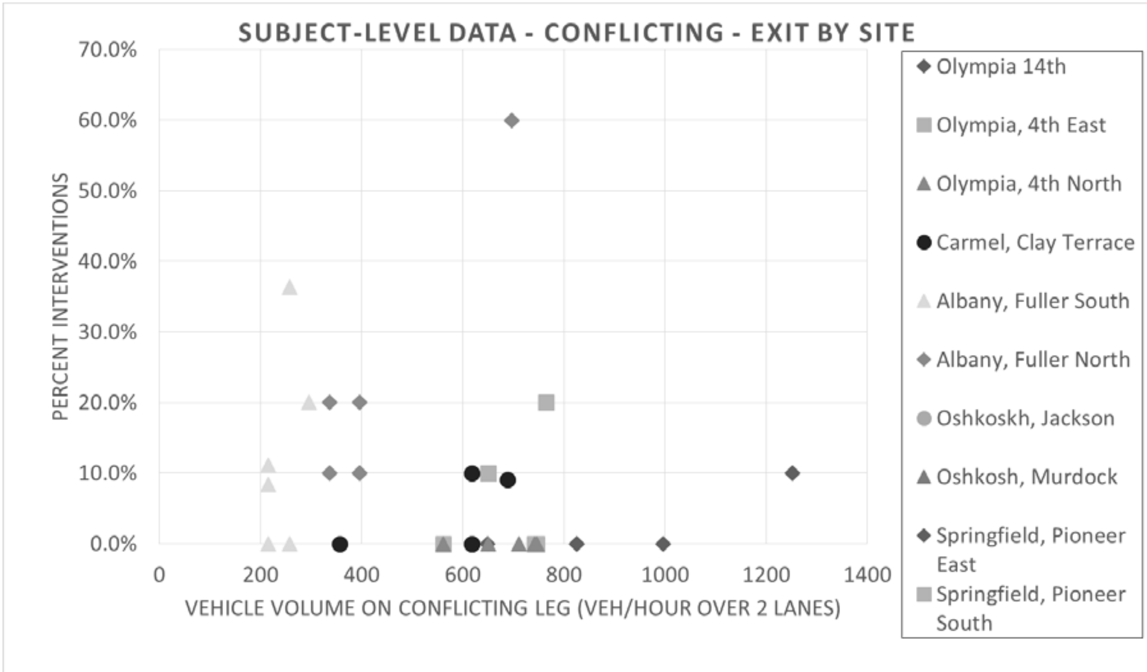

Figure 40. Plot. Percent intervention as a function of vehicle volume for individual sites- exit.

Exit interventions were generally higher and more spread out than entry interventions as shown in figure 40. No clear patterns were evident from the data. The following are the individual observations for each site. Olympia 14th generally had high volumes with a mix of interventions (0% to 10%). Olympia 4th East has mid-level volumes with a mix of interventions (0% to 10%). Olympia 4th North had mid to high volumes with all zero interventions. Carmel Clay Terrace had mid-level volumes with a mix of interventions (0% to 10%). Albany South Fuller had low volumes with a mix of interventions (0% to 36%). Albany North Fuller (channelized turn lane) had mid to low volumes with high interventions (10% to 60%). Oshkosh, Jackson has med volumes with a mix of interventions (0% to 30%). Oshkosh, Murdock has low volumes with a mix of interventions (0% to 20%). Springfield, East has mid to high volumes with mix of interventions (0% to 20%). Springfield, South has mid to low volumes with a mix of interventions (0% to 30%).

Observer Interventions by Leg (Sorted)

In addition to the interventions, a trained observer rated each crossing. Figure 41 shows the percentage of observer interventions by leg. The data are ordered from highest to lowest intervention rate, with exit legs shown in black and entry legs shown in gray. The channelized turn lane site (dashed) and the single-lane exit (black dotted) are also highlighted.

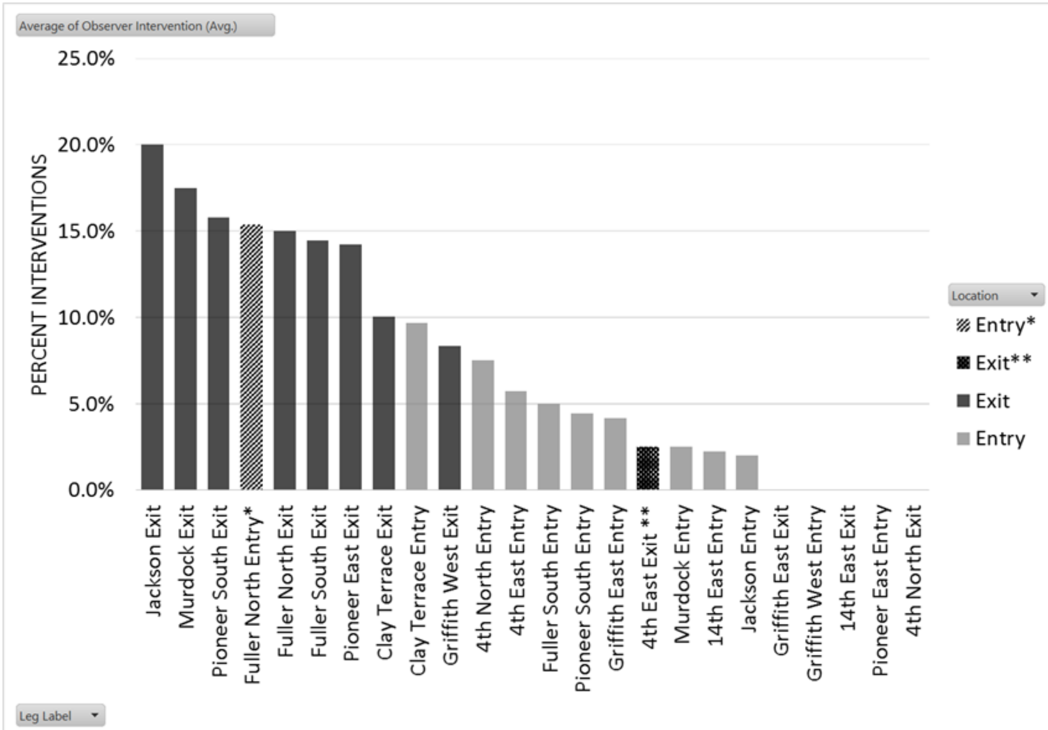

Figure 41. Chart. Average observer estimated intervention rates for each approach.

Many of the observer ratings seemed to agree with the COMS intervention ratings, although the observer ratings tended to be higher across the board. An outlier site is Clay Terrace Blvd. in Carmel, IN, where at the exit the observer estimated 10.0 percent interventions, while the COMS estimated only 3.8 percent. Also, at the entry the observer estimated 9.7 percent interventions, while the COMS estimated only 3.7 percent. The observer estimated seven of nine two-lane exit legs to be at 10 percent or greater interventions, with the remaining two at zero interventions. The 4th St. North exit in Olympia, WA, was reported as having zero interventions by both COMS and observer (uphill downstream of crosswalk). The 14th St. East exit in Olympia, WA, had zero interventions for the observer and 2 percent for the COMS. The observer estimated 9 of 10 entries to be below 10 percent interventions, and 5 to be below 5 percent intervention rate. The entry with the highest rate of interventions was the channelized turn lane site, which is consistent with the COMS ratings.

Direct Comparison of COMS and Observer

Table 8 shows a side-by-side comparison of COMS and Observer Interventions. The table is ordered by rank of COMS Interventions, with 1 being the leg with the highest rate of intervention and 24 being the lowest rate of intervention. The COMS and Observer rank columns are shaded with from high intervention (dark gray) to low intervention (very light gray).

Table 8. Side-by-side comparison of COMS and observer intervention rates for each approach.

Leg	Exit/ Entry	COMS Intervention percent	Observer intervention percent	COMS Intervention Rank	Observer intervention Rank
Fuller North Exit	Exit	21.7%	15.0%	1	5
Jackson Exit	Exit	16.0%	20.0%	2	2
Murdock Exit	Exit	15.0%	17.5%	3	3
Fuller North Entry*	Entry*	13.6%	15.3%	4	4
Fuller South Exit	Exit	12.9%	14.5%	5	7
Pioneer East Exit	Exit	12.2%	14.6%	6	6
Pioneer South Exit	Exit	11.4%	13.6%	7	8
Griffith West Exit	Exit	8.3%	8.3%	8	11
14th East Entry	Entry	7.1%	2.4%	9	18
4th North Entry	Entry	6.7%	6.7%	10	12
Griffith East Entry	Entry	4.3%	4.3%	11	14
Pioneer South Entry	Entry	4.2%	4.2%	12	15
Clay Terrace Exit	Exit	4.0%	10.0%	13	9
Clay Terrace Entry	Entry	3.8%	9.6%	14	10
4th East Exit **	Exit**	3.0%	2.9%	15	16
14th East Exit	Exit	2.4%	0.0%	16	23
4th East Entry	Entry	2.2%	4.4%	17	13
Pioneer East Entry	Entry	2.2%	0.0%	18	20
Jackson Entry	Entry	2.1%	2.1%	19	19
Fuller South Entry	Entry	1.7%	23.3%	20	1
Murdock Entry	Entry	0.0%	2.5%	21	17
Griffith West Entry	Entry	0.0%	0.0%	22	21
4th North Exit	Exit	0.0%	0.0%	23	22
Griffith East Exit	Exit	0.0%	0.0%	24	24

The COMS interventions agreed with those of the observer for the seven approaches with the highest interventions (percent COMS interventions over 10%, although the two raters placed them in a somewhat different order. The observer identified two additional sites as having a very high intervention (over 10 percent) at Clay Terrace Blvd. exit and Fuller South Entry (23.3%). For the last site, the COMS identified all these events as "risky events," but not as rising up to the level of intervention.

Of the 14 approaches with the lowest intervention rates (percent COMS Interventions less than 5%), the observer agreed with 11 of them. The remaining 3 had 9.6 percent, 10.0 percent, and 23.3 percent estimated observer interventions.

Figure 42 compares the two rating systems (observer and COMS percent interventions) by plotting the two results against each other, and showing the 45-degree line as a frame of reference. A linear regression analysis shows an R-squared of 0.50, and the corresponding trend line is shown in the graph. This trend is influenced greatly by the Albany, NY, outlier site. Without those outliers, the two ratings have a level of agreement above 80 percent.

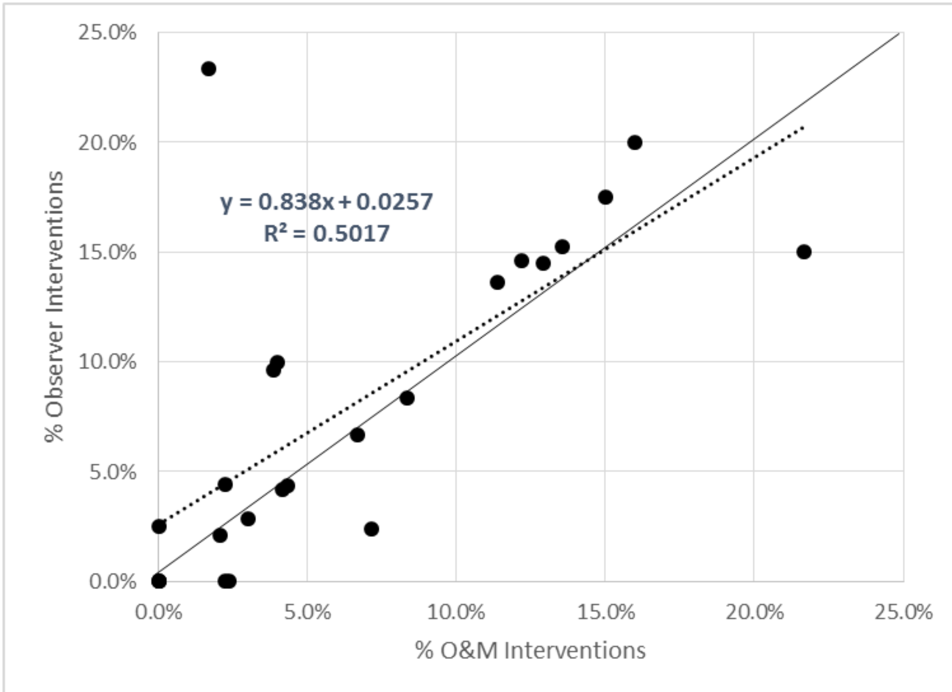

Figure 42. Graph. Comparison of observer and COMS percent interventions.

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