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

Human Factor Assessment of Traffic Control Device Effectiveness

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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)

FOREWARD

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/.

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NOTICE

QUALITY ASSURANCE STATEMENT

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16. Abstract
This volume is seventh in a series of seven. The other volumes in the series are: Volume I - Evaluation of Rectangular Rapid-Flashing Beacons (RRFB) at Multilane Roundabouts, 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, and Volume VI – Investigation of Crosswalk Design and Driver Behaviors. 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 examined the relationship between signing and marking of multilane roundabouts and the likelihood of erratic maneuvers, and thus conflicts and crashes. The report documents two different studies: (1) observation of erratic maneuvers and conflicts from overhead video recordings; and (2) an in-vehicle eye tracker study to investigate driver gaze patterns and gaze direction while traversing multilane roundabouts. The two most dominant contributing factors to erratic maneuvers appear to be (1) inconsistencies between lane use markings on the approach and those within the circulatory roadway, and (2) insufficient channelization for drivers when being shifted from the inside lane to the outside lane to exit. Drivers also were more likely to glance at markings than at signs.

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CHAPTER 1. INTRODUCTION

Prior research has shown roundabouts to have lower rates of severe and fatal crashes than signalized intersections and two-way stop-controlled intersections (Rodegerdts et al. 2007). However, isolated serious-injury and fatal crashes have occurred at roundabouts, as reported in Volume 4, Review of Fatal and Severe Injury Crashes at Roundabouts. Some multilane roundabouts have also been reported to have an unusually high occurrence of property damage-only crashes (Richfield et al. 2014, Bill et al. 2011). A possible explanation for these crashes, explored in this study, is that they may be attributable to traffic control devices such as signing and marking. Even though the severity of crashes at roundabouts may lower than that at traffic signals, the tendency for a high frequency of low-severity crashes to occur at some multilane roundabouts is an issue that warrants attention as roundabouts become more common.

OBJECTIVE

The objective of this research was to develop insights into the relationship between signing and marking of multilane roundabouts and the likelihood of erratic maneuvers that may lead to conflicts and crashes. To evaluate the performance of multilane roundabouts with respect to erratic maneuvers, the team performed two different studies: (1) observation of erratic maneuvers and conflicts from overhead video recordings; and (2) an in-vehicle eye tracker study to investigate driver gaze patterns and gaze direction while traversing multilane roundabouts. The two studies complemented each other in that, conceptually, the observation of erratic maneuvers and conflicts was a macroscopic study of a broad sample of vehicles across many sites, and the in-vehicle eye-tracker study was a pseudo-naturalistic study of driver eye movements at a subset of sites.

LITERATURE REVIEW

The majority of studies conducted on signs and pavement markings at roundabouts in the United States precede the Federal Highway Administration's 2009 Manual on Uniform Traffic Control Devices (MUTCD) (Hanscom 2009, Molino et al. 2007, Inman et al. 2006) and are based primarily on driver simulator experiments involving various sign types.

Few studies have used field-based measurements of before-and-after safety performance related to choices of signs and pavement markings. One of the few instances documented in the literature is at a site in Richfield, MN, where a two-lane roundabout replaced a signalized intersection in 2008. After the conversion, the roundabout experienced an unexpected number of property damage only (PDO) crashes. The city sought to identify potential contributory factors for the crashes as well as low cost solutions to the PDO crash problem. Signing and striping changes that were made included replacing fishhook arrows with standard arrows (with a dot to represent the central island), adding turn arrows and lane designation signs approximately 450 feet upstream of the yield line on all legs, extending the solid line from 50 feet to 250 feet upstream of the yield line, changing circulating lane striping to a 3-foot stripe/1-foot gap pattern with a 6-inch-wide stripe, lowering the mounting height of some signs, and increasing the size of the YIELD signs. Richfield et al. (2014) conducted an observational study at that roundabout using overhead video before and after the signing and striping changes were made between 2010 and 2011. They studied yield violations, lane change violations, turn violations, incorrect lane choice, wrong way movements, and stopping events. Results showed that, after the signing and striping changes, yielding violations decreased by 25 percent, turning violations decreased by 55 percent, and incorrect lane choice decreased by 59 percent. All reductions were significant at the 95 percent confidence level except for yield violations. These results were attributed to a combination of application of guidelines from the 2009 MUTCD and options for circulatory roadway striping taken from the National Cooperative Highway Research Program (NCHRP) Report 672, each intended to reinforce to drivers the importance of choosing the correct lane prior to entry. However, because all signing and striping changes were made at the same time, it is not possible to isolate the effects of individual changes.

From this literature review, it becomes evident that there is a gap in evaluating actual driver behavior in the field at different roundabouts, which may lead to a better grasp of actual conflict patterns and driver gaze patterns while traversing a roundabout. This research was therefore field-based in order to better understand actual driver behaviors as they relate to roundabout signing and marking.

EXPERIMENTAL APPROACH

Based on the current state of roundabout signing and marking practices, several key research questions were identified and used to develop the underlying research hypothesis, which informed this project's methodology, experimental design, and site selection. Two different methodologies were applied in this project: a video-based erratic-maneuver study of roundabouts, and an eye-tracker study of drivers in roundabouts. The video-based erratic maneuver study was a comprehensive study to identify the proportion of drivers making erratic maneuvers or causing vehicle-to-vehicle conflicts while driving through the roundabouts. The rate of these proxy safety events was then evaluated relative to the marking and signing at the studied two-lane roundabouts. The purpose of this study was to articulate targeted research questions for the eye tracker study. The eye tracker study was then intended to provide a more in-depth analysis of drivers' gaze patterns as they travel through a roundabout, and to identify what signs and markings drivers pay more attention to. The following sections describe the two experiments' methodologies in detail.

CHAPTER 2. METHODOLOGY: VIDEO-BASED ERRATIC MANEUVER STUDY

The first study in this task was a video-based study of vehicle erratic maneuvers and conflicts. The goal of the study was to understand patterns of conflicts and erratic maneuvers, and relate those to signing and marking at the studied roundabouts. Therefore, a data set containing video of roundabouts was identified. Erratic maneuvers were defined and categorized, as were types of signing and pavement markings. Data analysis consisted of reducing video data and identifying correlations between erratic maneuvers and signing and pavement markings, and is described in this section.

DATA SET

The team utilized available video of multilane roundabouts from prior research efforts, including NCHRP Project 03-65 (Roundabouts in the United States), NCHRP Project 03-100 (Evaluating the Performance of Corridors with Roundabouts), and video recorded for the research described in Volume 1 and Volume 2 of this broader FHWA research effort. The team inventoried the available video for data that could be used for this effort. Overall, the conflict study identified 164 hours of usable overhead video from 40 multilane roundabout legs in 10 U.S. cities, as listed in Table 1. Each leg is categorized by compass direction; a south leg, for example, is equivalent to a northbound approach.

Table 1. Sites for video-based erratic maneuvers study.

No.	ID	City	State	Intersection	Leg
1	Avon-1	Avon	CO	Avon Rd./Beaver Creek Blvd.	South
2	Avon-2	Avon	CO	Avon Rd./Benchmark Rd.	North
3	Avon-3	Avon	CO	Avon Rd./US 6	West
4	Avon-4	Avon	CO	Avon Rd./US 6	North
5	Avon-5	Avon	CO	Avon Rd./Beaver Creek Blvd.	East
6	Avon-6	Avon	CO	Avon Rd./Benchmark Rd.	South
7	Carmel-1	Carmel	IN	Illinois St./116th St.	East
8	Carmel-2	Carmel	IN	Illinois St./116th St.	South
9	Carmel-3	Carmel	IN	Hazel Dell Pkwy./126th St.	East
10	Carmel-4	Carmel	IN	Hazel Dell Pkwy./126th St.	North
11	Edwards-1	Edwards	CO	Beard Creek Rd./I-70 WB Ramps	North
12	Edwards-2	Edwards	CO	Beard Creek Rd./I-70 WB Ramps	East
13	Edwards-3	Edwards	CO	Edwards Access Rd./Miller Ranch Rd.	East
14	Edwards-4	Edwards	CO	Edwards Access Rd./I-70 EB Ramps	West
15	Edwards-5	Edwards	CO	Edwards Access Rd./Miller Ranch Rd.	South
16	Gig Harbor-1	Gig Harbor	WA	Harbor Hill Dr./Development Entrance	North
17	Gig Harbor-2	Gig Harbor	WA	Borgen Blvd./51st Ave. NW	East
18	Golden-1	Golden	CO	S. Golden Rd./Johnson St./16th Ave.	Southeast
19	Lynden-1	Lynden	WA	SR 539/Pole Rd.	North
20	Lynden-2	Lynden	WA	SR 539/Wiser Lake Rd.	North
21	Lynden-3	Lynden	WA	SR 539/Pole Rd.	South
22	Lynden-4	Lynden	WA	SR 539/Ten Mile Rd.	South
23	Malta-01	Malta	NY	SR 67/US 9	West
24	Malta-02	Malta	NY	SR 67/I-87 SB Ramps	East
25	Malta-03	Malta	NY	SR 67/I-87 SB Ramps	West
26	Malta-04	Malta	NY	SR 67/I-87 NB Ramps	West
27	Malta-05	Malta	NY	SR 67/I-87 NB Ramps	East
28	Malta-06	Malta	NY	SR 67/US 9	East
29	Malta-07	Malta	NY	SR 67/State Farm Blvd.	East
30	Malta-08	Malta	NY	SR 67 /State Farm Blvd.	West

No.	ID	City	State	Intersection	Leg
31	Malta-09	Malta	NY	SR 67/Kelch Dr.	West
32	Malta-10	Malta	NY	SR 67/Kelch Dr.	East
33	Olympia-1	Olympia	WA	4th Ave./Olympic Way	South
34	Olympia-2	Olympia	WA	14th Ave./Jefferson St.	North
35	Olympia-3	Olympia	WA	4th Ave./Olympic Way	East
36	Olympia-4	Olympia	WA	14th Ave./Jefferson St.	South
37	Oshkosh-1	Oshkosh	WI	Jackson St./Murdock Ave.	West
38	Oshkosh-2	Oshkosh	WI	Jackson St./Murdock Ave.	East
39	Hilliard-1	Hilliard	OH	Main St./Cemetery Rd.	West
40	Hilliard-2	Hilliard	OH	Main St./Scioto Darby Rd.	Southeast

Following the video inventory, a trained analyst watched the video and identified erratic maneuvers and conflicts. To keep the data reduction consistent, only one person conducted the video data reduction for the entire erratic-maneuver study.

TYPES OF ERRATIC MANEUVERS

For this study, erratic maneuvers were defined as any improper or illegal movement at the roundabout that did not impact other traffic. A conflict was defined as the subset of erratic maneuvers resulting in a near crash between two or more vehicles, and instances where vehicles needed to take evasive actions, such as rapid braking or lane changing, to avoid a crash. Due to a very low frequency of observed conflicts, conflicts were combined with erratic maneuvers to increase sample size. In addition, in most cases, due to camera view, it was not possible to separate conflicts from other erratic maneuvers. No crashes were observed within the video reviewed for this study.

The team identified the following five types of erratic maneuvers of particular interest for this study that drivers could perform when driving through a multilane roundabout. They are listed and described in Table 2. Other erratic maneuvers that can occur at multilane roundabouts, including wrong way maneuvers on the approach, wrong way maneuvers within the circulatory roadway, failure to yield on approach, and yielding within the circulatory roadway, were found to be infrequent and outside the scope of this study. Observations of these other erratic maneuvers are documented in Appendix A, but are not discussed further in this report. Only passenger cars were observed for erratic maneuvers for this study.

Table 2. Categories of erratic maneuvers.

Position	Erratic Maneuver Name	Description
Approach	Lane change	Driver enters the wrong lane of the circulatory roadway from the roundabout entry
Approach	Improper turn	Driver uses the left lane to make a right turn
Circulatory Roadway	Lane change	Driver changes lane within circulatory roadway
Circulatory Roadway	Improper turn	Driver exits from inside lane of circulatory roadway when not allowed by pavement markings
Circulatory Roadway	Lane straddle	Driver drives on lane lines

TYPES OF SIGNING AND PAVEMENT MARKINGS

For each observed roundabout, the team collected an inventory of signs and markings at roundabout entry approaches and circulatory lanes using available photos in Google Street View. Nine types of signs and three types of pavement markings were included in the study, as listed in Table 3. The table includes designations from the 2009 MUTCD as appropriate, although in some cases the signs at individual sites were not compliant with the 2009 MUTCD. This study did not look at the effect of variations within a single sign type (e.g., variations of the W2-6 Circular Intersection Sign).

Table 3. Roundabout signs and pavement marking types.

Type	Name
Sign	Circular Intersection Sign (W2-6)
Sign	Advance Lane Control Sign (R3-8)
Sign	Destination Sign (e.g., D1-1d)
Sign	Roundabout Directional Arrow (R6-4)
Sign	One Way Sign (R6-1)
Sign	Yield Ahead Sign (W3-2)
Sign	Yield Sign (R1-2)
Pavement marking	Lane Striping
Pavement marking	Lane Use Marking (normal arrows or fish-hook arrows)
Pavement marking	Yield Line

DATA ANALYSIS

The data reductionist observed approximately one hour of video for each site, with the exception of the two Hilliard sites, for which 13 hours of video were available for each site and were analyzed separately. In each case, the approach volume, circulatory roadway volume, and frequency of erratic maneuvers were normalized into hourly rates over the observed time period.

For each of the roundabout approaches, the flow rate of vehicles entering the roundabout (approach volume in vehicles per hour, calculated as a rate over the period of observation) and the flow rate of circulating vehicles passing in front of the entry (circle volume in vehicles per hour, calculated as a rate over the period of observation) were counted. In addition, the number of vehicles causing any of the erratic maneuvers was recorded. From those counts, the percentage of erratic maneuvers for each type of erratic maneuver was calculated by dividing the number of vehicles causing that particular type of erratic maneuver by the volume observed.

Pavement Marking and Erratic Maneuvers

The goal of the analysis regarding erratic maneuvers and lane marking was not to provide a comprehensive safety audit of each location, but rather to provide a high-level identification of trends related to pavement markings that can be generalized to design practice.

Available multilane roundabout video was screened to identify locations with erratic maneuvers as described in this study. At those sites, the team focused on the layout of pavement markings such as lane-use arrows, lane striping, and channelization striping, and attempted to identify trends regarding pavement markings and erratic maneuvers. Pavement markings were observed using aerial photos available from Google Earth, and the details of each site review are provided in Appendix A. Dates of the aerial photos were variable but were generally from 2012 (the year of the majority of the video used for this study) or as near to it as possible; dates are indicated in Appendix A.

Lane Control Signing and Pavement Marking

The team created an inventory of the existence, location, and count of lane-control signs and lane-use pavement markings at each of the roundabout approaches to see whether the count and type (markings versus signing) would have an effect on erratic maneuvers. The study sites were categorized by number of sets of lane-control signs and lane-use markings on the roundabout approach. The team then tallied the rate of erratic maneuvers for each lane-control designation.

Volume and Percentage of Erratic Maneuvers

The team examined whether there was a relationship between the number of erratic maneuvers observed and the average observed flow rate on the approach and circulatory roadway.

CHAPTER 3. METHODOLOGY OF THE EYE-TRACKING STUDY

The eye-tracking experiment was a pseudo-naturalistic study in which participants drove on a test route through several roundabouts while wearing an eye tracker. The study is described as pseudo-naturalistic because the environment and interactions with other vehicles and pedestrians were as they would have occurred naturally, but the experimenter determined the route that the participants drove. The route was designed to include particular intersections and maneuvers, but all other interactions with vehicles, pedestrians, and the environment along the route were naturalistic.

INDEPENDENT VARIABLES

Data for several independent variables were collected by the eye-tracking equipment and are listed and described in Table 4. In a true naturalistic study, many different independent variables can be selected based on the question the researcher intends to answer, and are limited only by what data was collected. For this experiment, the research team wanted to determine what drivers glanced at, where they glanced, and from which part of the roundabout they made these glances. Therefore, the following variables were defined and pulled from the eye-tracker data.

Table 4. Eye-tracking study independent variables.

Variable	Description (values)
Objects of Interest	The object category at which the drivers' eyes were directed (traffic, pedestrians, signs, markings, pedestrian-related signs and markings)
Marking and Sign Type	Per table 3
Vehicle Location	Location of vehicle at time of gaze (approach, entrance, circle, exit)
Number of Vehicles	Estimated number of vehicles in the roundabout at the time a glance occurred

Objects of Interest

One research goal was to determine the objects at which participant drivers gazed while traversing the roundabouts. Objects of interest were grouped into five main categories: traffic, pedestrians, markings, signs, and pedestrian-related markings and signs. Crosswalks and pedestrian crossing signs were put into this last category because their purpose is not to assist in navigating the roundabouts, but to alert drivers to possible pedestrian encounters, so they form a separate semantic class. The items in each object of interest category are listed in Table 5.

Table 5. Objects of interest.

Category	Object of Interest
Traffic	Vehicles in or near the roundabout
Pedestrians	Pedestrians in or near the roundabout
Markings	Lane Striping (circulatory roadway)
Markings	Lane Use Marking (circulatory roadway and approach)
Markings	Yield Line
Signs	Circular Intersection Sign (W2-6)
Signs	Destination Sign (e.g., D1-1d)
Signs	Roundabout Directional Arrow (R6-4)
Signs	Lane Control Sign (R3-8)
Signs	One Way Sign (R6-1)
Signs	Yield Ahead Sign (W3-2)
Signs	Yield Sign (R1-2)
Pedestrian-related Signs and Markings	Crosswalk Striping
Pedestrian-related Signs and Markings	Pedestrian Crossing & Yield to Pedestrian Signs (S1-1, W11-2, R1-6)

Marking and Sign Type

To analyze eye behavior with respect to marking and sign type, the categories of traffic, pedestrians, and pedestrian-related signs and markings were removed, and the category of markings and signs was divided into subcategories for marking and sign types. Those categories are listed in Table 3.

To further differentiate between the types of lane marking in the roundabout, the lane striping within the circulatory roadway was divided into three categories: right (outer) edge line, center lane line, and left (inner) edge line. This was done because it was determined that participants used the different lane lines for different reasons. Most glances toward the right edge line marking occurred before the participant entered the roundabout, and this marking acted similarly to a yield line. However, when within the circulatory roadway, participants tended to glance toward the center lane line and left edge line for guidance and staying within their lane.

Roundabout Location

The roundabouts included in the eye-tracker study in Carmel, IN had less signage and fewer markings than those in Hilliard, OH. The roundabouts in Carmel, IN had pavement markings on approach and at the entrance to the circulatory roadway that showed indications of wear (i.e. they had not recently been reapplied). The roundabouts in Hilliard, OH had pavement markings that had been more recently applied and showed fewer indications of wear. Therefore, the research team examined the differences in eye glance behavior between the two locations.

DEPENDENT VARIABLES

Data for several dependent variables were collected by the eye-tracking equipment, and are listed and described in Table 6.

Table 6. Eye-tracking study dependent variables.

Variable	Description (values)
Glance Count	How many times participants looked at an object. A glance was defined as any instance in which the gaze point remained on a particular object for at least two video frames (~69 ms).
Fixation Time	The length of time between saccades. Saccades are rapid eye movements that quickly change the point of fixation. These can be voluntary, but also occur reflexively any time the eyes are open, even while fixating on a target. (Purves, 2001)
Dwell Time	The duration in milliseconds that a glance remained directed at a particular object. Dwell time is the sum of all saccades and fixation times that occurred while the gaze remained directed at a particular object.

PARTICIPANTS

Participants were recruited using flyers posted in each of the locations where testing occurred, as well as through word-of-mouth. A total of 21 participants completed the eye-tracking study. Participants ranged in age from 18 to 72 years old, with a median age of 39. Twelve males and nine females participated. Participants had to successfully complete a screening questionnaire over the phone to be eligible for participation. Participants had to be at least 18 years old, hold a valid driver's license, and not have any medical conditions or taking any medications that might make it unsafe for them to drive. Participants were compensated $50.

EQUIPMENT

The study used a ViewPoint eye tracker, a head-mounted system that uses infrared lights and cameras mounted on a plastic frame to track the movement of the wearer's eyes (Figure 1). The eye tracker also includes a forward-facing color camera to record the scene in front of the wearer. After calibration, the eye tracker provides a video recording of the scene with the wearer's gaze point overlaid on the photo, as well as the XY coordinates of the gaze point and fixation times, among other variables. A screenshot is shown in Figure 2.

The frames are connected to a laptop with a cable that runs behind the wearer's right ear. This cable is clipped to the wearer's shirt to prevent pulling on the frames, and allows unrestricted movement of the wearer's head. The system calculates eye movement with an accuracy of between 0.25 and 1 degrees of visual arc, and a spatial resolution of approximately 0.15 degrees of visual arc.

Figure 1. Photo. ViewPoint eye tracker goggles.

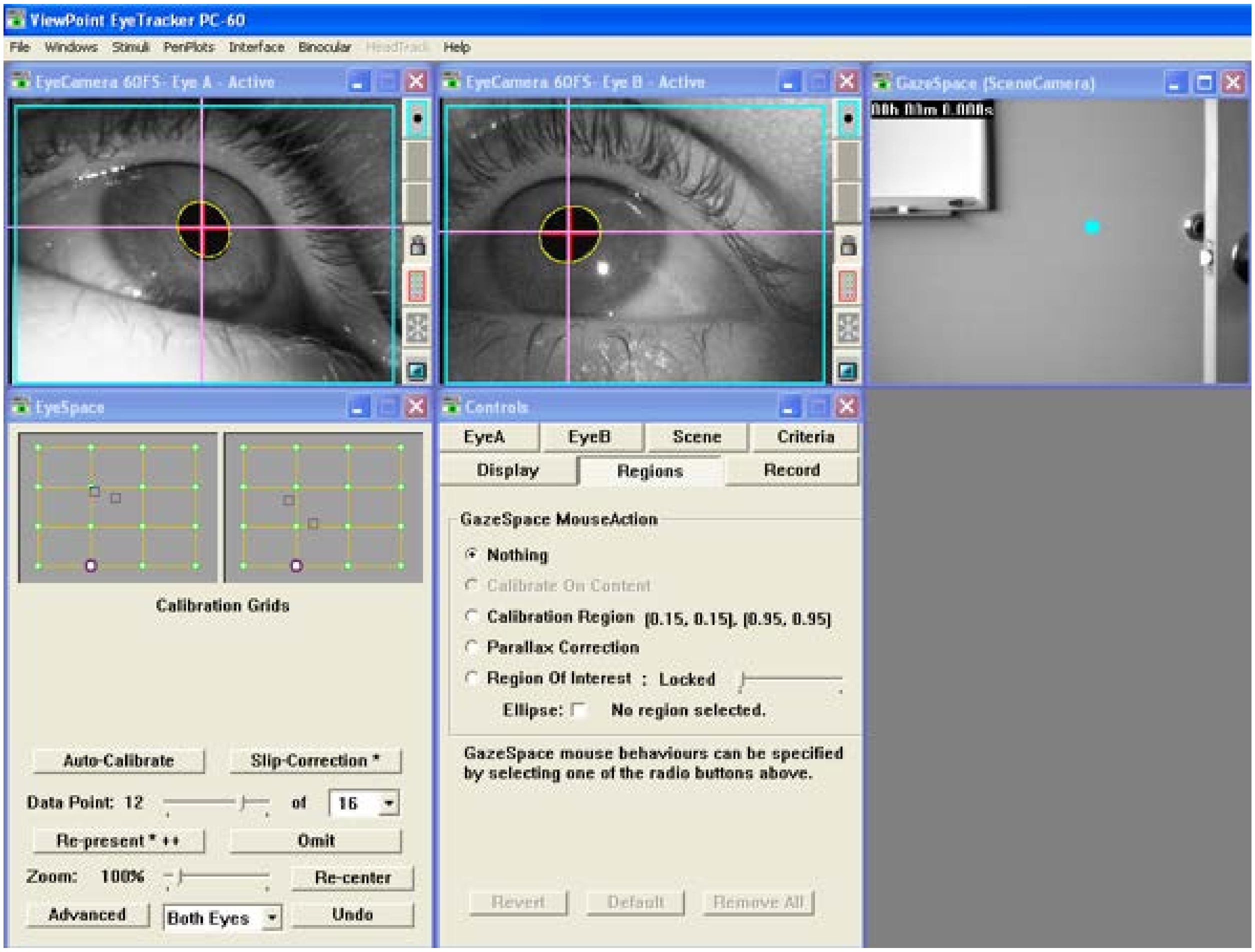

Figure 2. Screenshot. ViewPoint eye tracker software.

LOCATIONS

The study was conducted in two locations: Carmel, IN and Hilliard, OH. These locations were selected for their high density of roundabouts. A total of nine different roundabouts were included in the study, four in Carmel, IN and five in Hilliard, OH. Eight were two-lane roundabouts, and one was a single-lane roundabout with one two-lane approach (designated as a through-left lane and a right-turn-only lane). Routes were designed so participants performed 21 different movements through these roundabouts: 5 left turns, 3 right turns, 3 U-turns, and 10 through movements (see Appendices E and F for experiment details).

EXPERIMENTAL PROCEDURE

Participants were instructed to meet the research team in a parking lot near the test route at their scheduled time. Upon arrival, participants were greeted by an experimenter who administered the informed-consent form, which they were asked to read and sign.

After completing the paperwork, participants were escorted to the vehicle, familiarized with the vehicle controls (e.g., seat, mirror, and steering adjustments), and fitted with the eye-tracker, which was then calibrated. An experimenter explained the instructions for the study: that the experimenter would provide directions for the travel route, to refrain from casual conversation, and to drive safely. The participant was then instructed to begin the drive and directed along the test route. The participant was offered no guidance for lane selection, and only told which way to turn at an upcoming roundabout.

Depending on traffic conditions, driving the test route took participants approximately 40 minutes to 1 hour. Upon return to the starting point, participants filled out a post-drive questionnaire (See Appendix B for questionnaire and Appendix C for detailed results.) asking about their experience and comfort level with driving through roundabouts, and they were compensated and dismissed. The driving routes for Hilliard, OH, and Carmel, IN, are provided in Appendices D and E respectively.

DATA REDUCTION

Glances

A ‘glance’ was defined as the duration of time that a participant’s gaze rested on an object of interest. A glance did not include any transitional movements from one glance to the next, unless the gaze simply moved from one part of an object to another (such as scanning one side of a crosswalk to the other). A glance would begin as soon as the gaze point stopped on an object, and end just before the gaze point moved away from the object. A glance also had to last for at least two video frames (~69 ms) to be included. Any glance that lasted less than two video frames was indistinguishable from transitional or random eye movements due to the limitations of the eye tracker.

Data reductionists began analyzing glances for a particular roundabout when the participant was approximately 73.2 m (250 ft) upstream from the first roundabout-related sign or marking. A circular intersection sign (W2-6) indicating the presence of a downstream roundabout was usually the first sign on the approach. Data reductionists stopped analyzing glances for a roundabout once the participant vehicle reached the exit crosswalk. Figure 3 shows an example of these points.

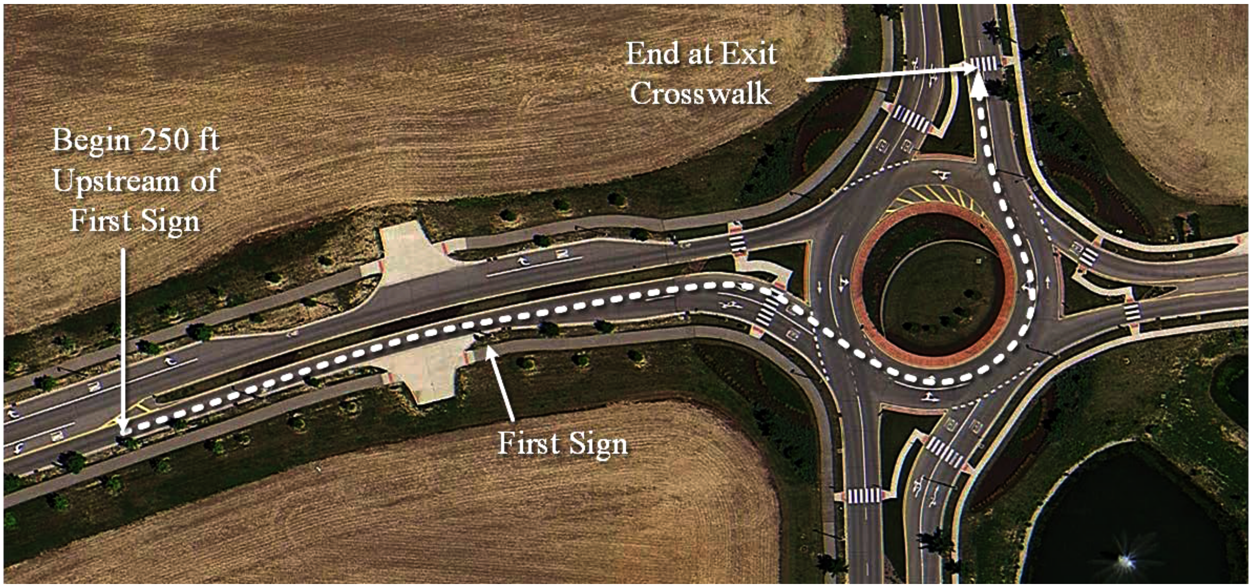

Figure 3. Diagram. Example segment for eye glance data collection and analysis.

When data reductionists found glances to the objects of interest, they entered the times at which the glance began and ended into a spreadsheet. They also entered contextual information that existed at the beginning of the glance, such as which lane the participant was in, where in the roundabout they were located, etc.

Locations

To examine how drivers' glance patterns changed as they drove through the roundabouts, each roundabout was conceptually divided into four areas (the approach, entrance, circle, and exit) as shown in the example in Figure 4. These areas were always based on the participant's perspective, and not on cardinal direction. The entrance and exit areas included the crosswalk in that leg, and the area between the circle and the crosswalk. Additional location information was collected for glances at pedestrians (e.g., whether they were on sidewalk, crosswalk, or splitter island).

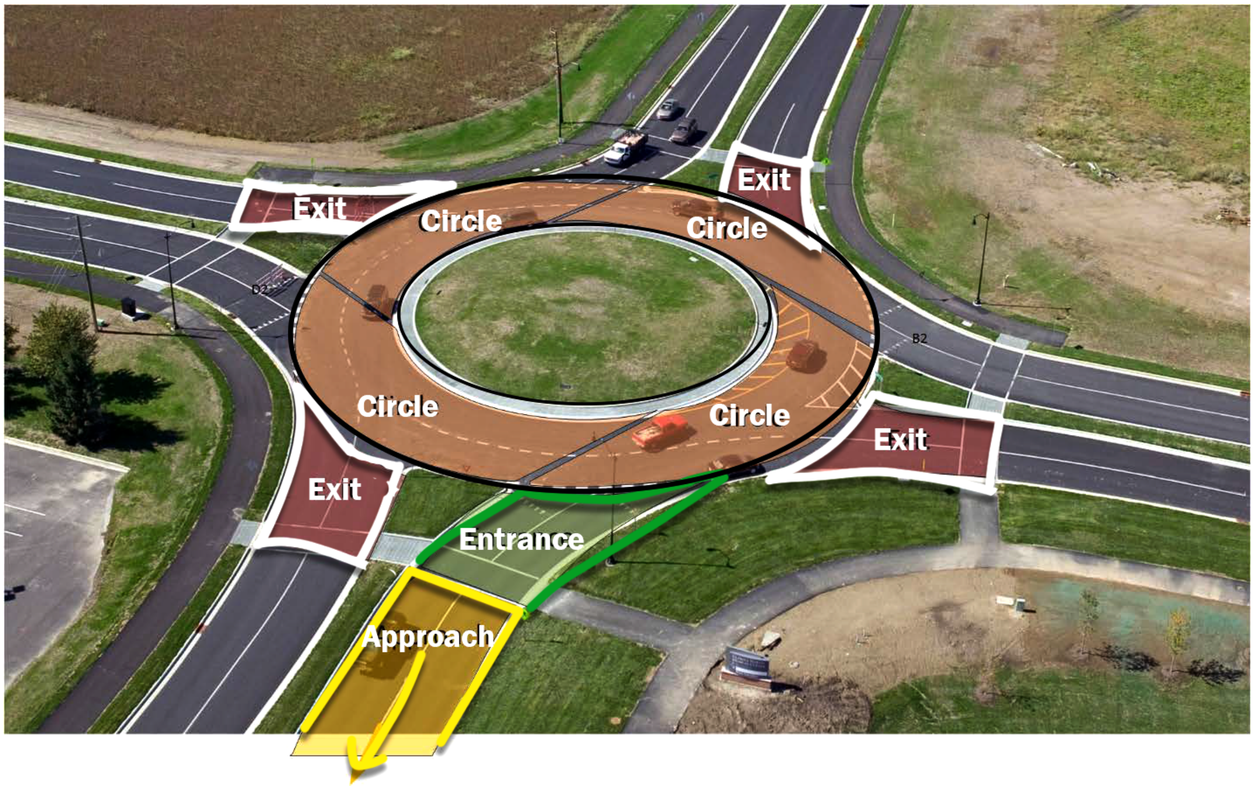

Figure 4. Diagram. Segmentation of the roundabouts for tracking vehicle and object locations.

Number of Vehicles

Data reductionists estimated the number of vehicles present for each glance using the eye-tracker video. Any vehicle that was visible in the eye tracker video, and was within the circulatory roadway, or areas between the circulatory roadway and crosswalks, were counted.

CHAPTER 4. RESULTS

This section presents results for the video-based erratic maneuver study, followed by the eye-tracking study. Table 7 lists the roundabouts used for the video-based erratic maneuver study. The table includes roundabout location, approach, and average frequency of each type of these erratic maneuvers per entry, and circulating volume for the video hours observed.

Table 7. Roundabout Approach and Circulatory Roadway Erratic Maneuvers

ID	Approach Volume (vph)	Approach Lane Change (percent)	Approach Turn (percent)	Circulatory Roadway Volume (vph)	Circulatory Roadway Lane Straddle (percent)	Circulatory Roadway Lane Change (percent)	Circulatory Roadway Turn (percent)
Avon-1	493	4.1	0.0	496	3.4	1.0	1.2
Avon-2	627	4.0	0.0	342	10.2	0.0	1.0
Avon-3	410	4.6	0.0	529	0.9	14.0	2.1
Avon-4	667	2.2	0.0	311	14.8	5.8	0.0
Avon-5	416	11.5	6.0	966	0.5	5.0	0.9
Avon-6	557	5.4	0.0	327	1.5	12.5	2.1
Carmel-1	849	0.6	0.1	231	10.5	6.1	0.0
Carmel-2	1585	2.0	0.0	545	2.2	0.7	0.4
Carmel-3	118	15.3	0.0	1344	0.1	0.0	0.1
Carmel-4	127	5.5	0.0	800	0.1	4.8	0.0
Edwards-1	692	2.6	0.0	224	1.8	0.0	0.0
Edwards-2	217	0.9	0.0	417	0.0	0.0	0.2
Edwards-3	172	1.7	3.5	592	0.0	1.5	0.3
Edwards-4	657	0.8	0.0	397	2.5	3.0	0.3
Edwards-5	245	9.0	0.0	791	3.0	4.9	0.0
Gig Harbor-1	318	2.5	0.0	69	0.0	0.0	0.0
Gig Harbor-2	1002	1.2	0.0	229	6.0	10.0	3.6
Golden-1	543	0.0	0.0	334	2.1	1.8	12.9
Lynden-1	632	0.6	0.2	144	0.0	0.0	2.1
Lynden-2	613	1.0	0.0	160	0.0	0.0	0.0
Lynden-3	808	1.0	0.0	26	0.0	0.0	0.0
Lynden-4	688	0.0	0.1	47	0.0	0.0	4.3
Malta-1	682	0.7	0.1	496	2.8	4.4	0.8

ID	Approach Volume (vph)	Approach Lane Change (percent)	Approach Turn (percent)	Circulatory Roadway Volume (vph)	Circulatory Roadway Lane Straddle (percent)	Circulatory Roadway Lane Change (percent)	Circulatory Roadway Turn (percent)
Malta-2	950	0.6	0.0	34	0.0	0.0	0.0
Malta-3	393	2.3	0.0	389	7.0	8.2	0.0
Malta-4	703	1.4	0.0	47	0.0	9.0	8.0
Malta-5	350	2.9	0.0	859	5.0	8.0	0.0
Malta-6	343	0.9	0.0	709	2.0	6.0	3.0
Malta-7	682	2.1	0.0	73	0.0	0.0	0.0
Malta-8	602	6.0	0.0	127	7.0	12.0	0.0
Malta-9	541	1.5	0.0	53	6.4	11.0	7.5
Malta-10	495	7.1	0.0	106	8.5	10.4	0.9
Olympia-1	532	3.9	0.0	812	0.0	0.0	0.1
Olympia-2	642	1.7	0.0	704	9.2	3.8	0.1
Olympia-3	1078	1.0	0.1	538	0.0	4.5	0.4
Olympia-4	209	1.0	0.0	718	0.0	0.0	0.0
Oshkosh-1	602	0.0	0.0	729	0.0	2.4	0.2
Oshkosh-2	448	1.8	0.0	593	3.0	8.2	0.0
Mean	571	2.9	0.3	429	2.9	4.2	1.4
50th Percentile	580	1.8	0.0	393	1.7	3.4	0.2
75th Percentile	682	4.0	0.0	676	4.6	7.5	1.2
90th Percentile	879	6.3	0.1	804	8.7	10.6	3.8

ERRATIC MANEUVERS VS. PAVEMENT LANE MARKINGS

The team reviewed the lane markings at sites with high rates (rates in the 75^{th} percentile or higher among sites studied) of the following maneuvers: approach lane change, circulating lane change, circulating turn, and circulating lane straddle. The research team identified three major observations in the relationship between pavement markings and erratic maneuvers, which are discussed here.

First, the large number of erratic maneuvers in the circulatory roadway (circulating lane change, circulating turn, and circulating lane straddle) at some sites can most likely be attributed to inconsistencies between the lane-use marking at the approach and that in the circulatory roadway. For some roundabouts, no indication was provided that a left lane of a two-lane approach was a left-turn only lane. In some cases the lack of left-turn-only designation appears to be because there were no lane use markings. In other cases, the lack of left-lane-only designation appears to be because the roundabout approach has a through arrow incorrectly in the left lane. Presumably, this is because designers were concerned drivers would misinterpret the left-lane indication arrows and go the wrong way in the roundabout. If the left lane were incorrectly marked as a through lane, drivers starting in the left lane and intending to go through the roundabout must make a lane change, turn, or straddle to exit. These erratic maneuvers can likely be minimized by using lane-use signing and marking throughout the entire roundabout consistent with the guidance in the MUTCD. This study observed no wrong-way maneuvers in the circulatory roadway, so the concern that proper lane marking leads to wrong-way turns may be unwarranted.

Second, at a number of sites, circulating lane straddle and circulating lane change maneuvers appear to be correlated with the presence of inadequate channelization (through spiraling) to shift drivers from the inside lane to the outside lane for some left-turn maneuvers. This spiraling is illustrated in the MUTCD in a number of figures, including figures 3C-4 and 3C-5. Several roundabouts with an abnormally high proportion of these erratic maneuvers had very short spirals, often no more than one or two vehicle lengths. Some drivers followed the alignment of the edge of the truck apron rather than the stripes, resulting in abrupt lane shifts when exiting. Although further analysis was not conducted as part of this research, it may be possible to minimize these erratic maneuvers by using longer and smoother spirals to minimize the amount of change in curvature drivers encounter. In addition, although it could not be confirmed through this study, using physical channelization may also prove more effective, especially during inclement weather when markings could be obscured by rain or snow. Possible avenues to explore include extending the truck apron to form the spiraling rather than using spiraling pavement markings alone, and using the channelization techniques associated with the turbo-roundabout design technique being used in the Netherlands and elsewhere.

Finally, some of the circulating lane straddle maneuvers could be attributed to the alignment of lanes between the entry and circulatory roadway. This path alignment is discussed at length in Section 6.5.4 of NCHRP Report 672. Some lane straddles were observed when the drivers were not in the immediate presence of other vehicles, allowing the driver to assume a path similar to a ‘fastest path’ alignment through the circulatory roadway. It is unknown whether the same drivers would stay in their lane in the presence of other drivers, thus making this particular trend appear less consequential than the trends discussed previously.

ERRATIC MANEUVERS VS. TRAFFIC VOLUME

The team examined whether there was a relationship between the number of erratic maneuvers and the average observed flow rate on the approach and circulatory roadway. Figure 5 shows the percent of total approach erratic maneuvers by approach volume and the percent of total circle erratic maneuvers by circle volume. In general, as the traffic volume increased, the percent of erratic maneuvers decreased. However, since the R^2 is very low in both cases (0.04 and 0.16, respectively), no relationship can be concluded across the wide variation in geometries presented in the full data set.

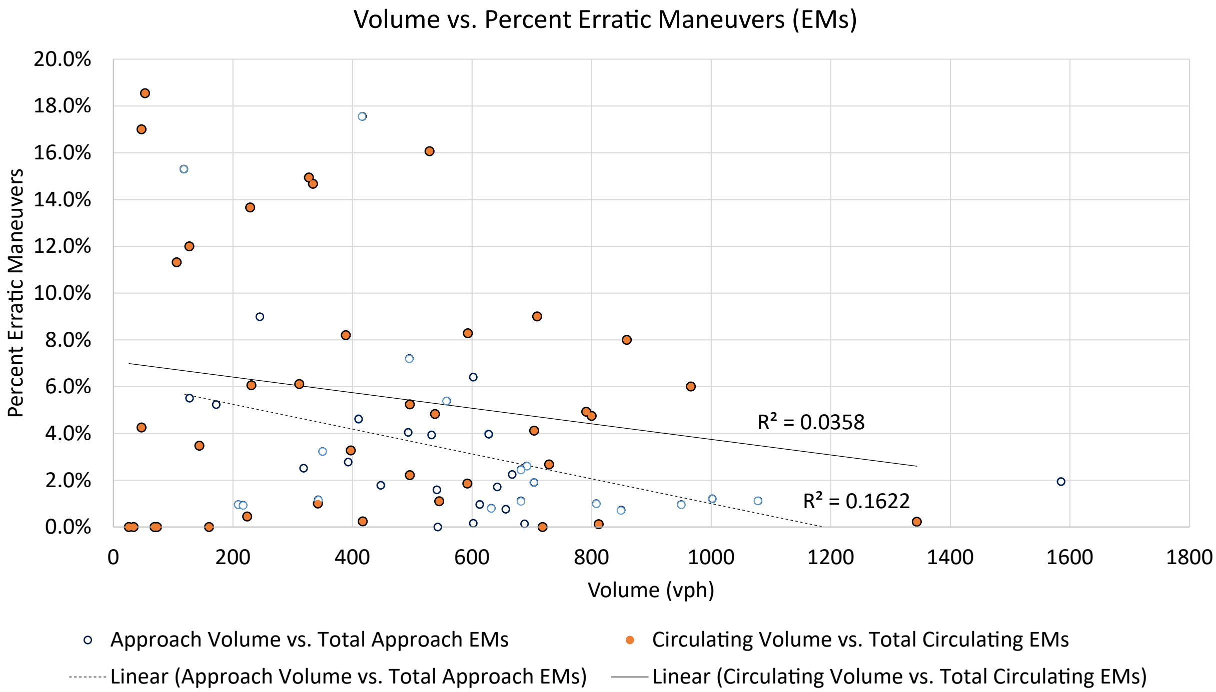

Figure 5. Graph. Traffic volume vs. percentage of erratic maneuvers observed on the approach and in the circle.

The team conducted a more focused examination at the two Hilliard roundabouts where more time periods of data were available and where the differences in geometry and driver population across all study sites could be narrowed. Figure 6 shows the percent of total circulatory roadway erratic maneuvers by circulatory roadway volume, and Figure 7 shows the percent of approach erratic maneuvers by approach volume. In both cases, no relationship can be seen with the percentage of circulating lane straddles versus circulating volume or approach lane straddles versus approach volume. However, circulatory roadway lane changes decrease with an increase in circulating volume with a reasonably strong negative exponential trend (R^2 of 0.58), and approach roadway lane changes also decrease to a lesser extent with an increase in approach volume also decrease to a lesser extent (R^2 of 0.16). This suggests that as volumes increase, particularly in the circulatory roadway, drivers appear to be paying more attention to proper lane selection for completing their desired turning movements.

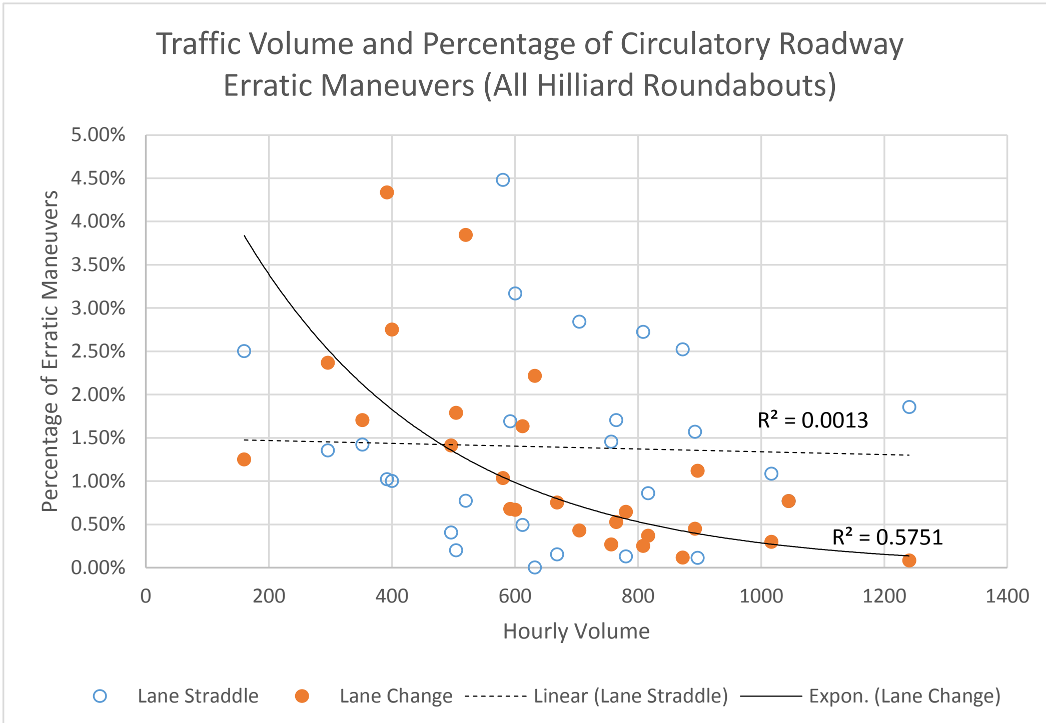

Figure 6. Graph. Traffic volume vs. percentage of erratic maneuvers observed in the circulatory roadway (all Hilliard roundabouts).

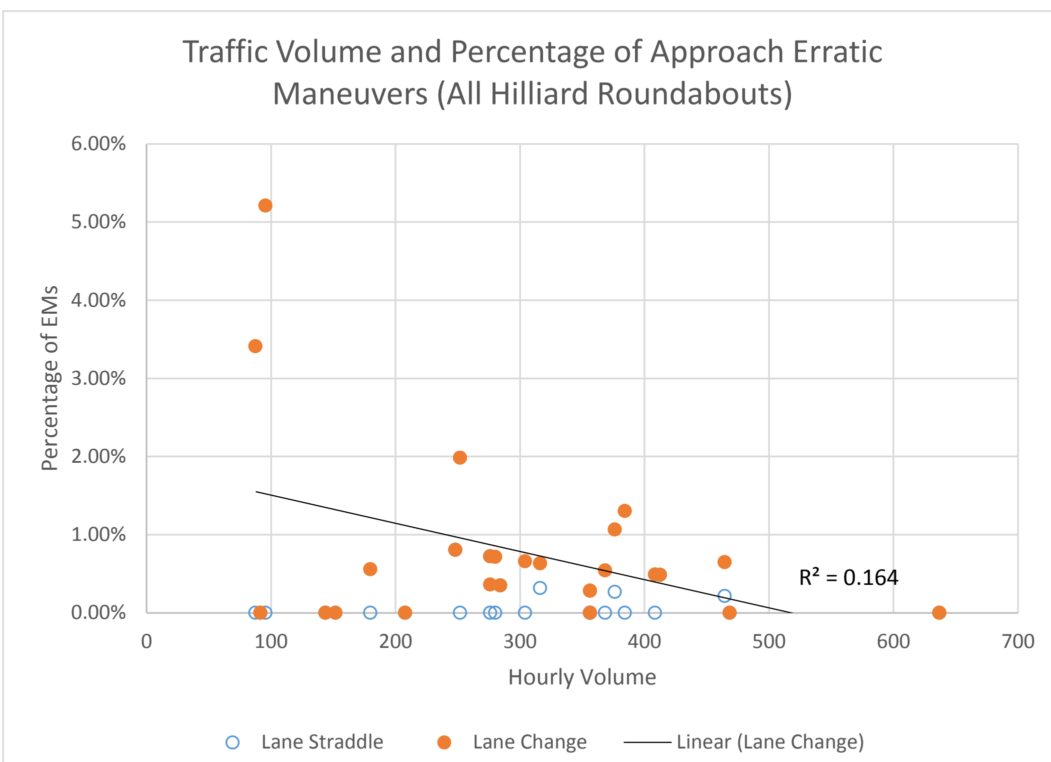

Figure 7. Graph. Traffic volume vs. percentage of erratic maneuvers observed on the approach (all Hilliard roundabouts).

EYE-GLANCE BEHAVIOR VS. OBJECT OF INTEREST

Eye glance behavior was compared among the five categories of objects of interest: traffic, pedestrian, markings, signs, and pedestrian-related markings and signs.

Percent of Glances and Dwell Time

Figure 8 shows the total glance count and the total dwell time of glances for each category of object of interest, and Figure 9 shows the percentage of total dwell time by object of interest. Out of the 1,759 glances that were reduced (which added up to over 14 minutes of total dwell time), glances at traffic were most common, and accounted for over half of all the time participants spent glancing at objects of interest in the roundabouts. Pedestrian-related signs and markings accounted for over a quarter of all glances and nearly a quarter of all dwell time. Glances towards crosswalks accounted for most of these. Glances toward other markings and signs made up less than a third of all glances, and less than a quarter of all dwell time. Very few pedestrians were encountered during data collection, resulting in only 19 total glances at pedestrians. Pedestrian glances occurred in eight different instances among six different participants.

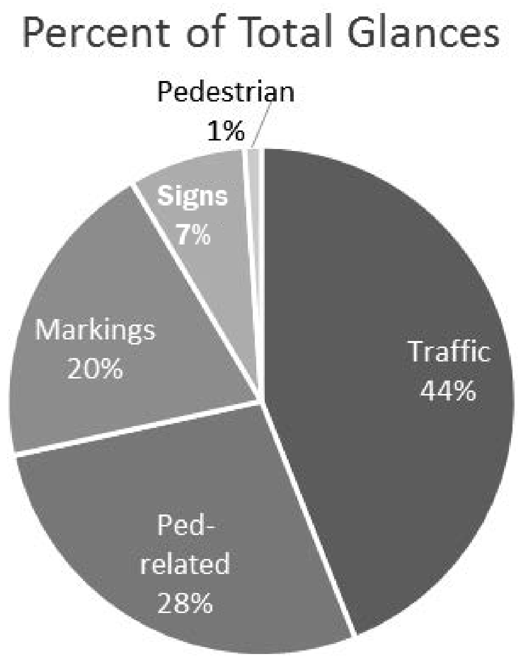

Figure 8. Pie Chart. Percentage of the total number of glances by object of interest.

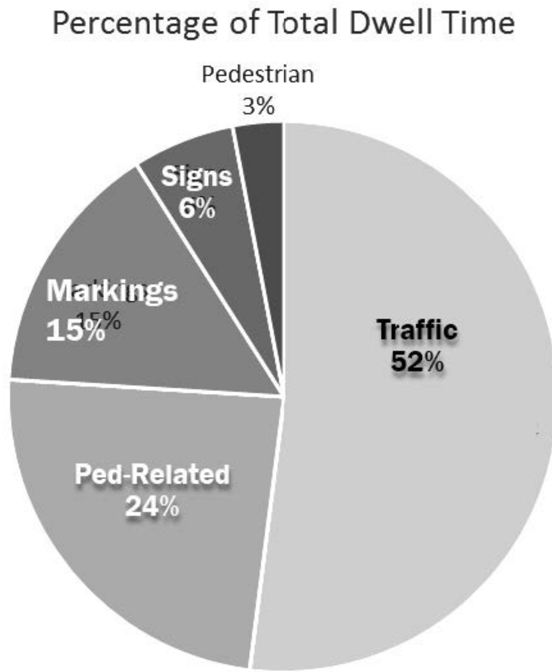

Figure 9. Pie Chart. Percentage of the total dwell time by object of interest.

Duration of Dwell and Fixation Times

Figure 10 shows the mean dwell time, and Figure 11 the mean fixation time, for each object of interest. Fixation time is the length of time between saccades, and dwell time is the total amount of time a participant's gaze was focused on an object. A single dwell time can comprise several fixations.

The mean dwell time for glances at pedestrians was far longer than that of any other object of interest. Glances toward pedestrians lasted more than 1 s on average, twice as long as glances toward other vehicles, and roughly three times as long as glances toward markings or signs. Additionally, pedestrian glances had a longer mean fixation time (89 ms) than any other object of interest. Mean fixation times for the remaining objects of interest were very similar; all fell within 7 ms of each other.

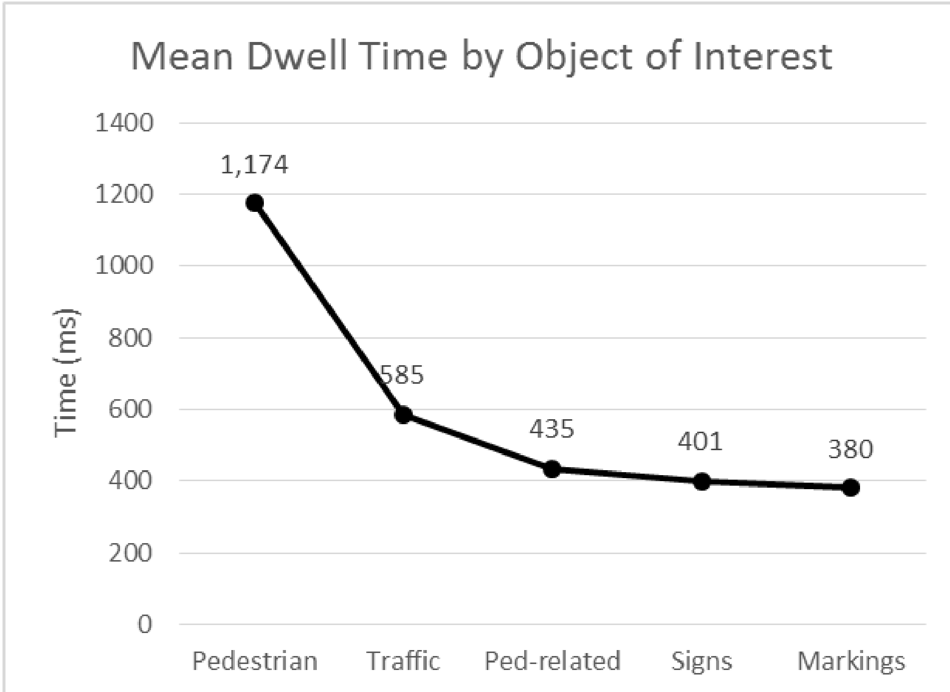

Figure 10. Graph. Mean dwell time by object of interest.

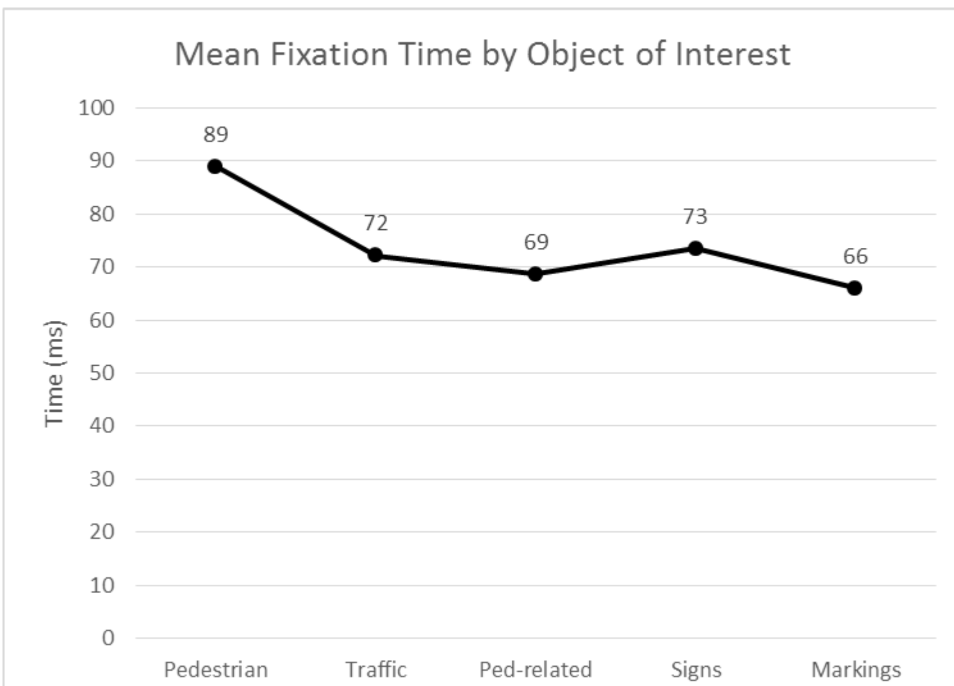

Figure 11. Graph. Mean fixation time by object of interest.

EYE-GLANCE BEHAVIOR VS. MARKING AND SIGN TYPE

To make comparisons among the pavement markings and signs intended to help drivers navigate through roundabouts, the objects of interest of traffic, pedestrians, and pedestrian-related signs and markings were removed from the analysis, and the remaining objects were categorized as described in table 3.

This left a total of 493 glances. Figure 12 shows the total number of glances and the mean dwell time for each of the markings and sign types. The majority of glances were toward lane use markings in the circulatory roadway, and center lane striping in the circulatory roadway. Together, these two markings accounted for nearly 54% of glances to signs and markings. These two markings also appear directly in front of the participant's vehicle, which may help explain the large number of glances toward them.

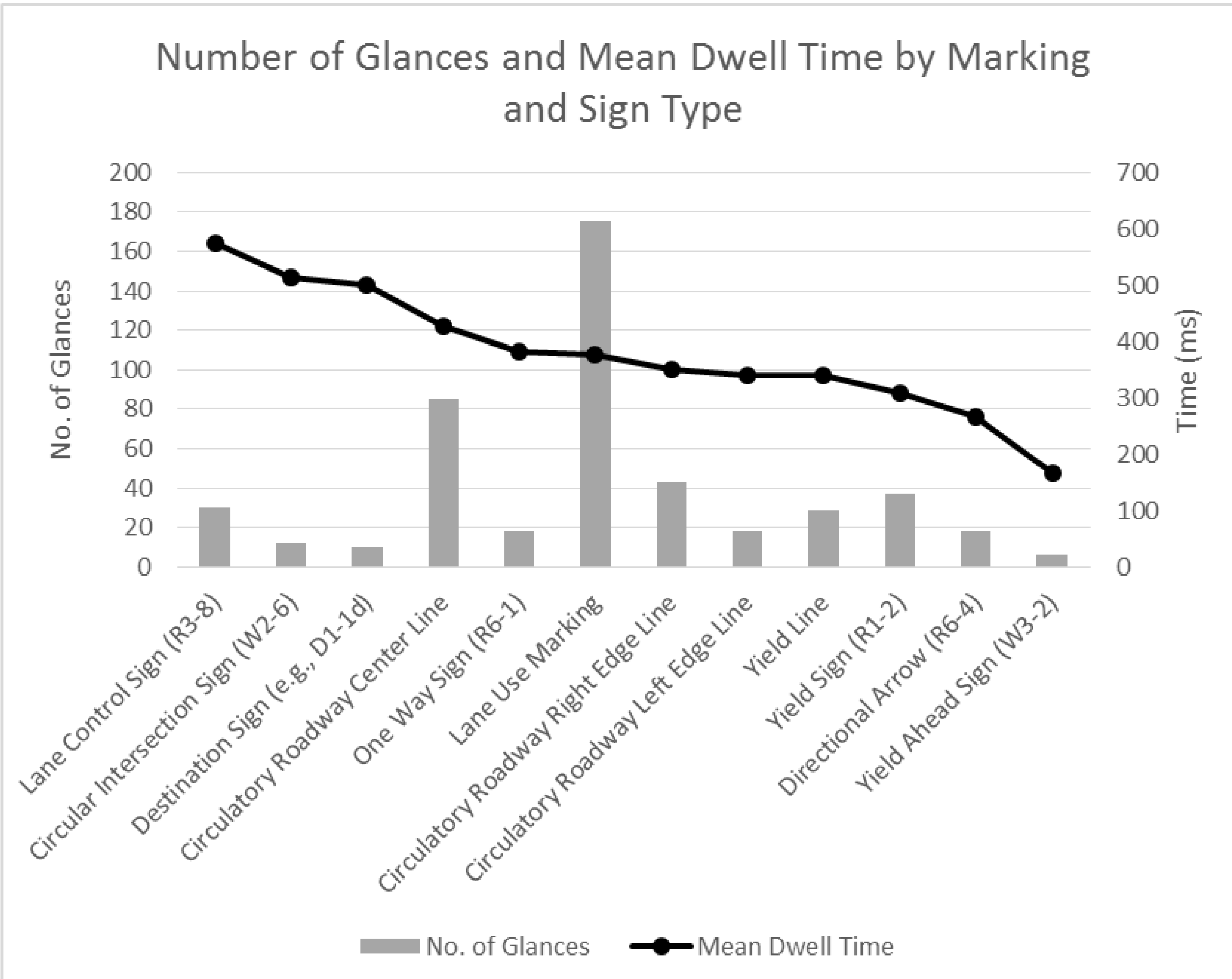

Figure 12. Chart. Total glances and mean dwell time by marking and sign type.

Yield-ahead signs had the lowest mean dwell time at 166 ms. This may suggest that these signs are easily recognized and understood. Lane control signs had the highest mean dwell time at 575 ms. This may suggest drivers need a longer amount of time in order to interpret the information on the sign. By comparison, the mean dwell time for circulatory roadway lane use markings—the pavement marking equivalent of lane control signs—was 376 ms, 199 ms shorter than the mean dwell time for lane control signs.

EYE GLANCE BEHAVIOR VS. VEHICLE LOCATION

Figure 13 shows the percentage of total glances toward the different marking and sign types by the vehicle's location: the approach, entrance, or circle. Signs and markings, which accounted for less than 1% of glances are not shown. The entrance was defined as the area between the crosswalk and the circle, where drivers yield before entering the circle (section A2 in figure 4). During the approach, participants glanced toward the lane use markings in the circulatory roadway far more than any other sign or marking. While in the entrance, participants made many fewer glances at signs and markings in general compared to when they were in the approach or the circle. This is likely due to the fact that they were only in the entrance for a short time, and needed to spend that time looking for traffic. Of the glances that were made in the entrance, most were toward the lane striping in the circulatory roadway. While in the circle, participants glanced at the lane striping most often, followed next by the lane use markings.

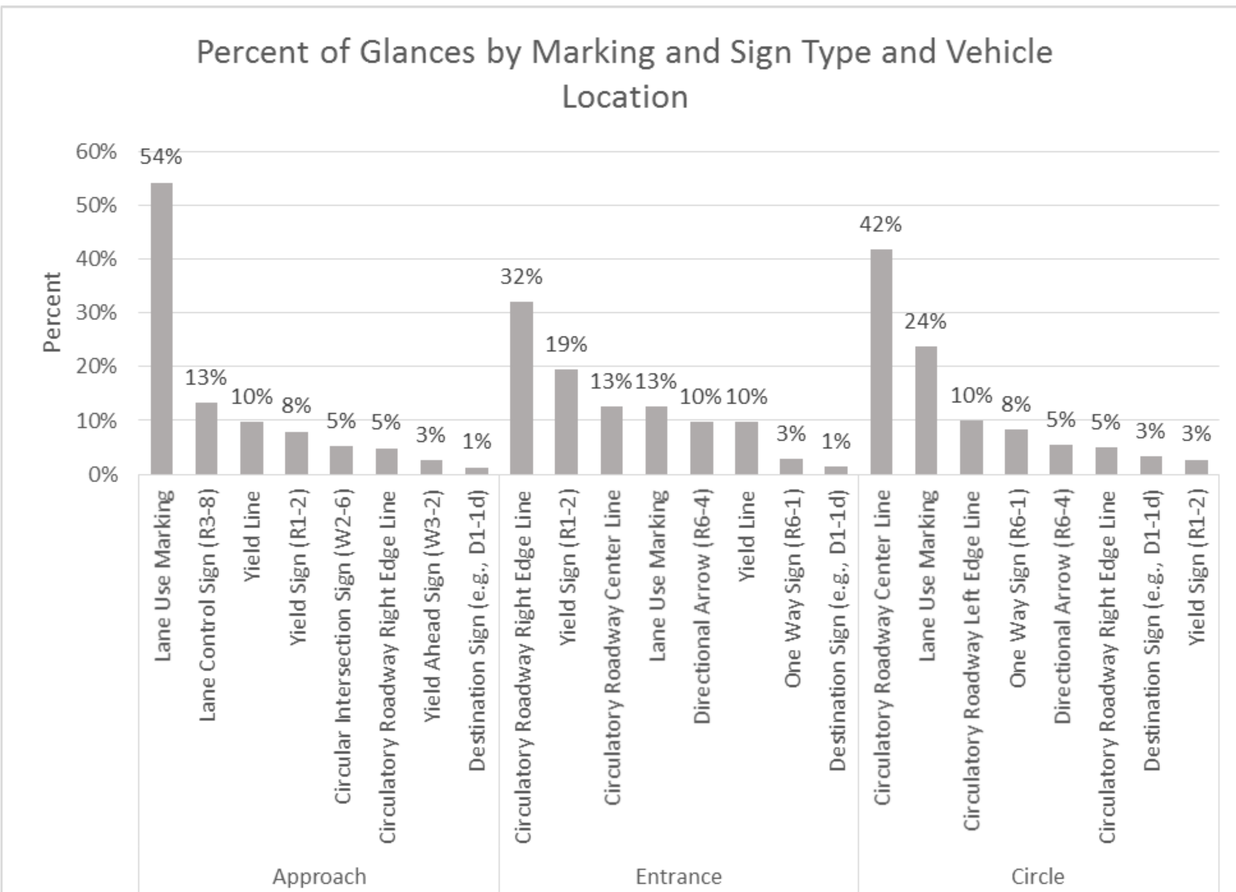

Figure 13. Chart. Percent of total glances by marking and sign type and vehicle location.

Figure 14 shows the mean dwell time for each sign and marking type by the vehicle location. Marking and sign types with the highest percentage of glances are highlighted. Those with fewer than three total glances were excluded; as such a small sample likely does not accurately represent mean dwell times. While in the approach, glances toward lane control signs had the highest mean dwell time. While in the entrance, glances toward yield lines had a considerably longer mean dwell time than those at other marking and sign types. Glances toward destination signs had the longest mean dwell time for drivers in the circle.

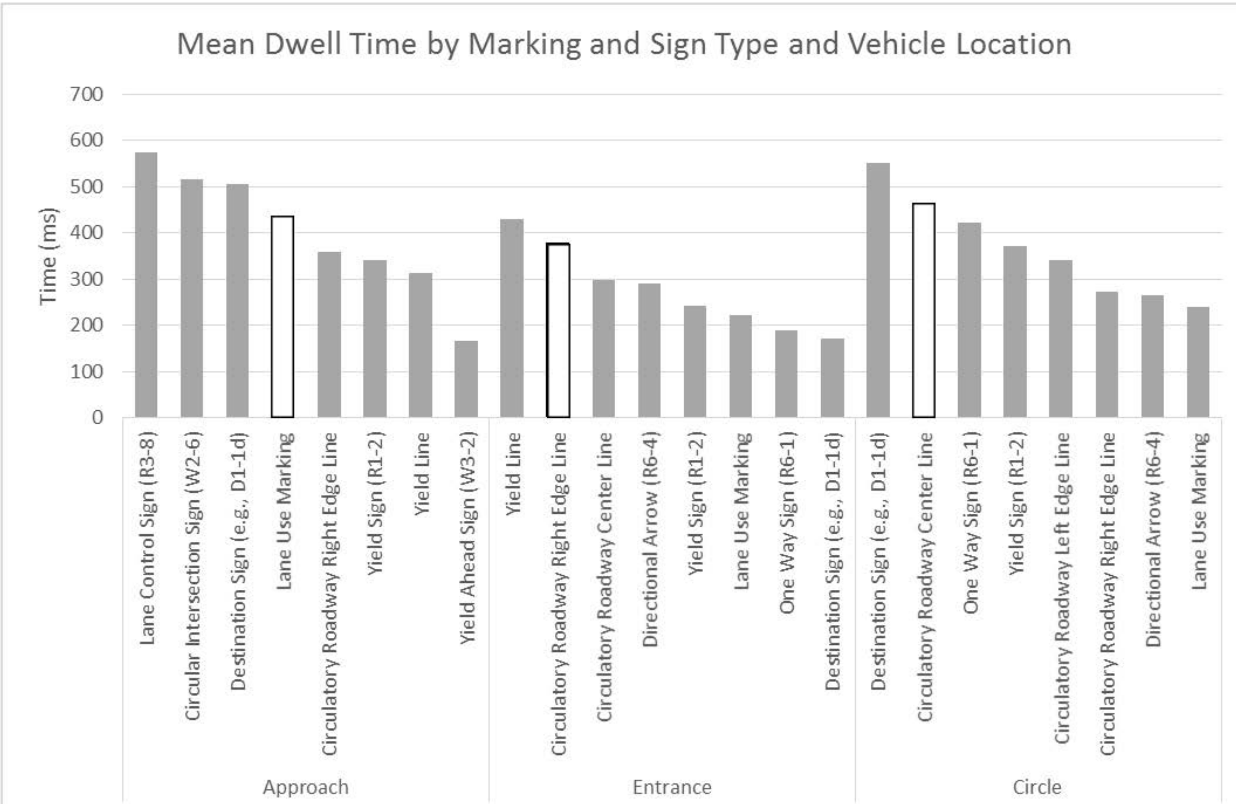

Figure 14. Chart. Mean dwell time by marking and sign type and vehicle location

EYE-GLANCE BEHAVIOR VS. ROUNDABOUT LOCATION

Figure 15 shows the percentage of total glances for roundabouts by category of object of interest in Carmel, IN and Hilliard, OH. Drivers in Carmel, IN made a much higher percentage of glances toward traffic than those in Hilliard, OH, while Hilliard drivers made a higher percentage of glances toward markings, and pedestrian-related signs and markings. However, the roundabouts in Hilliard tended to have more markings and pedestrian-related signs, which likely explains this difference. For example, roundabouts in Hilliard often had lane use markings within the circulatory roadway, and some intersections had overhead pedestrian-crossing signs, whereas those in Carmel did not. The percentage of glances towards signs and pedestrians was roughly the same between the two roundabout locations.

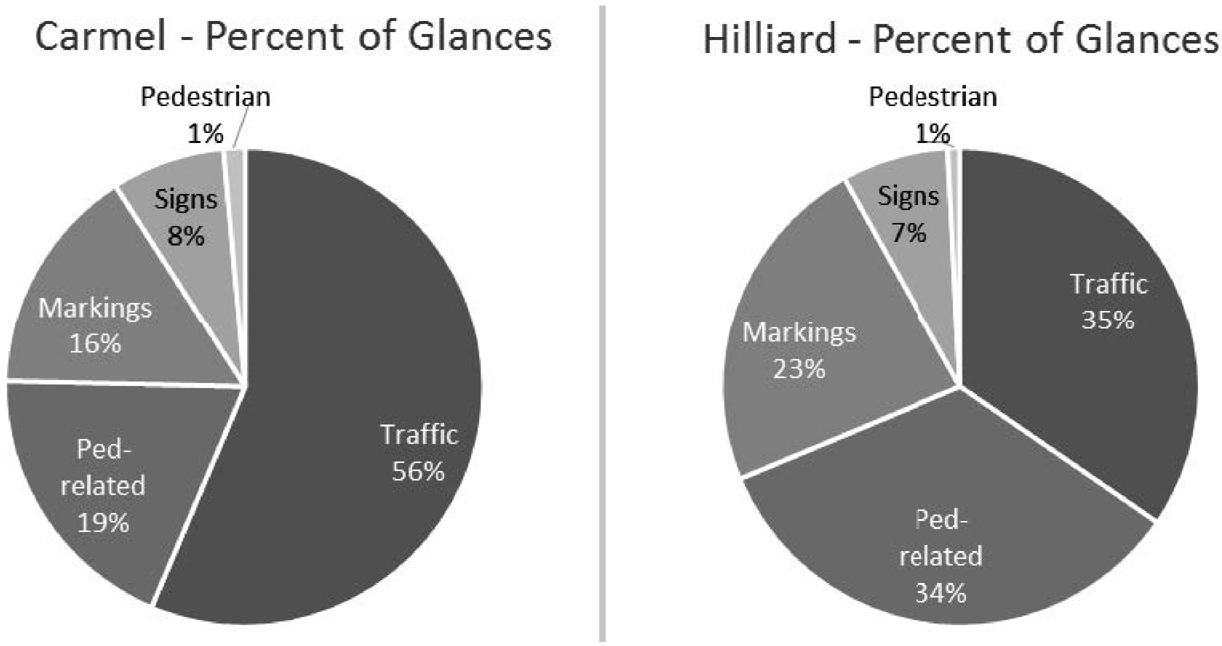

Figure 15. Charts. Comparison of total glances by object of interest between Carmel, IN and Hilliard, OH.

Figure 16 shows the percentage of glances by marking and sign type for the two locations (markings and sign types with less than 1% of glances are not shown). The 22% fewer glances that drivers in Hilliard, OH made toward traffic seem to be spread out among the next four most-glanced-at objects. Among crosswalks, circulatory-roadway lane use markings, circulatory-roadway lane striping, and yield-to-pedestrian signs, Hilliard, OH drivers made 23% more glances than drivers in Carmel, IN.

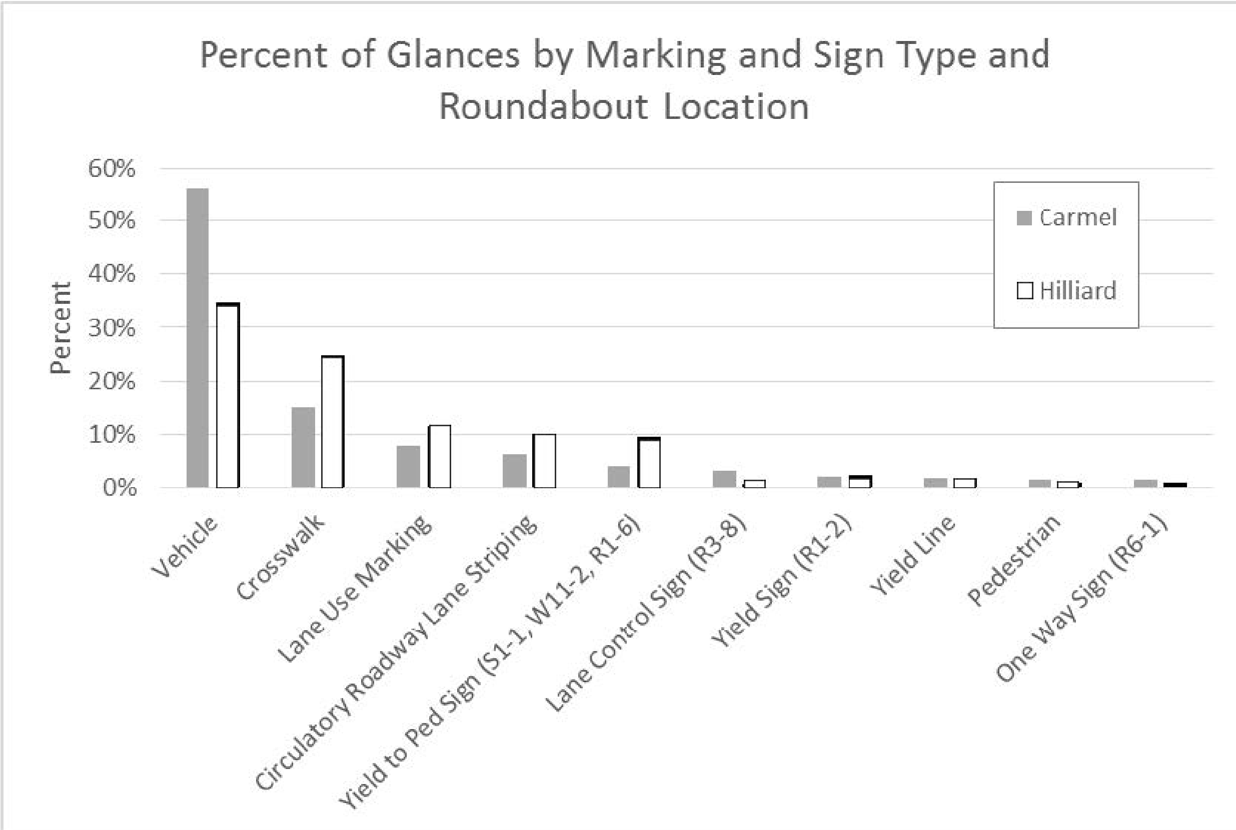

Figure 16. Chart. Percentage of total glances by marking and sign type and roundabout location.

EYE-GLANCE BEHAVIOR VS. NUMBER OF VEHICLES

Glances toward traffic comprised a larger percentage of glances in Carmel, IN, than in Hilliard, OH. That was not because there was more traffic in Carmel, IN; there was less traffic per glance in Carmel, IN than in Hilliard, OH. Carmel averaged 1.8 vehicles in the roundabout per glance, and Hilliard averaged 2.4.

Figure 17 shows the percent of all glances for each roundabout location versus the number of vehicles in the roundabout at the time the glance occurred. Most glances that occurred in Carmel, IN, (about 30%) occurred when there were no other vehicles within the roundabout. Only about 17% of glances that occurred in Hilliard, OH, occurred when there were no other vehicles in the roundabout. Glances that occurred when there were four or more other vehicles in the roundabout made up a larger percentage of glances that occurred in Hilliard, OH, than in Carmel, IN. These results suggest that traffic volume is not the only factor affecting number of glances towards traffic.

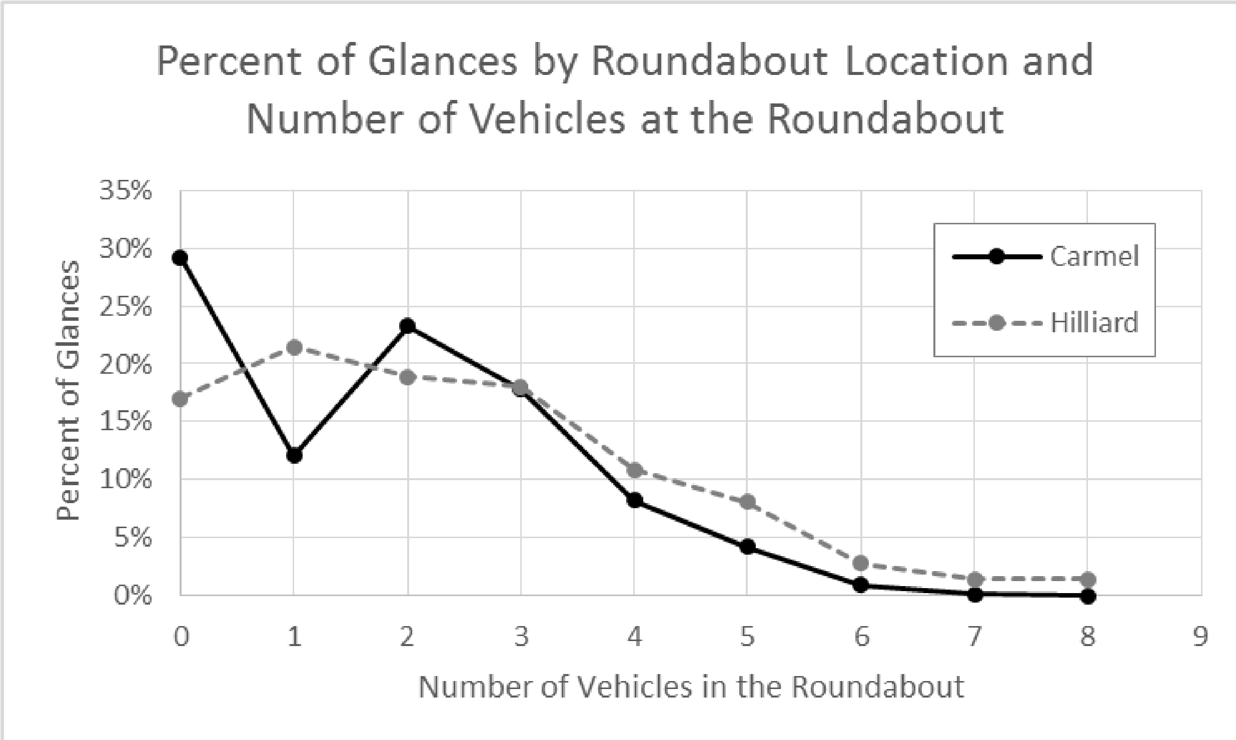

Figure 17. Graph. Percent of glances by roundabout location and number of vehicles in the roundabout.

Drivers in the two roundabout locations share a trend with respect to the object of interest and mean dwell times (Figure 18). In both locations, pedestrians had the longest mean dwell times, and signs and markings the shortest mean dwell times. However, drivers in Carmel, IN had longer dwell times for every category of object of interest than those in Hilliard, OH. It is possible that the roundabouts in Hilliard, OH—particularly those along Main St.—had more visually complex scenes with more signs, markings, and traffic than those in Carmel, IN, which caused drivers in Hilliard, OH to frequently shift their gaze, reducing mean dwell times.

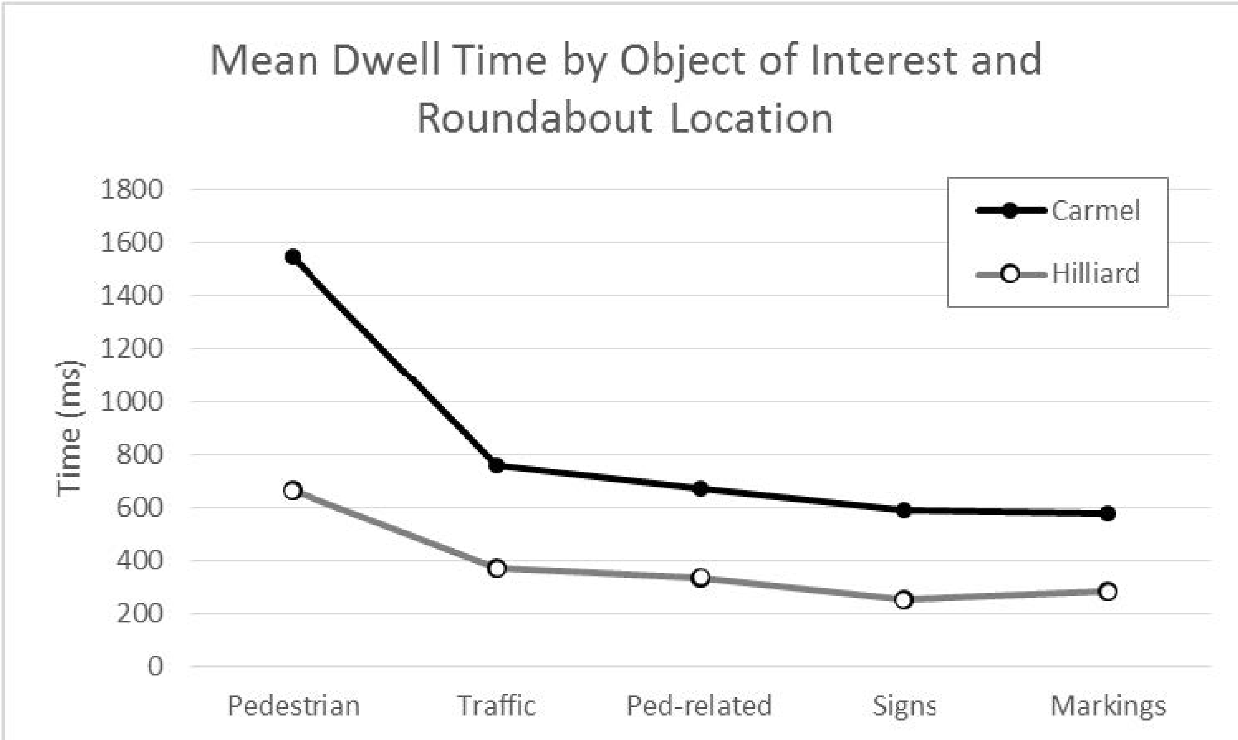

Figure 18. Graph. Mean dwell time by object of interest and roundabout location.

A similar effect was found when comparing drivers' mean fixation time between the cities, as shown in Figure 19Figure 19, where drivers in Carmel, IN tended to have longer mean fixation times than those in Hilliard, OH. One notable exception was mean fixation time for pedestrian glances, which was virtually identical between the two cities and had a difference of only 1.29 ms.

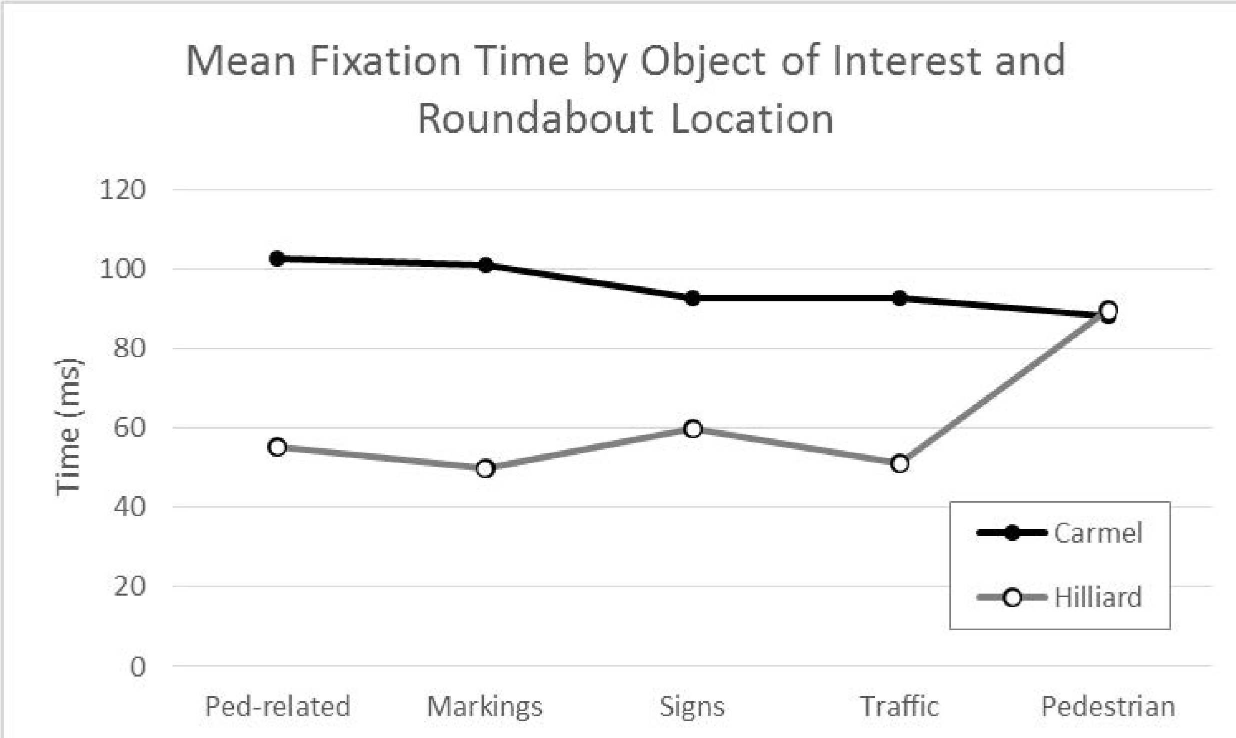

Figure 19. Graph. Mean fixation time by object of interest and roundabout location.

DISCUSSION OF EYE GLANCE RESULTS

When considering the combined data from Carmel, IN and Hilliard, OH, it appears that drivers do not spend a great deal of time looking at roundabout-related signs or markings. Together, they accounted for only 28% of all glances tracked for this study, which only included glances toward a specific list of objects. When drivers do glance at markings and signs related to the roundabouts, they look at markings (350 glances) 2.7 times as much as at signs (131 glances). A similar pattern occurred for the pedestrian-related signs and markings. Drivers glanced at crosswalks a total of 360 times, and at yield-to-pedestrian/pedestrian-crossing signs 125 times.

On average, drivers spent slightly less time glancing at markings (380 ms) than at signs (401 ms). However, this effect varied between the two roundabout locations. Drivers in Hilliard, OH had a slightly longer mean dwell time (30.3 ms longer) for markings than for signs, while drivers in Carmel, IN, had a slightly longer mean dwell time (13 ms longer) for signs than markings. When comparing glances on approach at lane control signs and lane use markings that present similar information to the driver, the difference in dwell times between markings and signs was more pronounced. When the vehicle was approaching the roundabout, glances at lane control signs lasted, on average, 575 ms, about 32% (140 ms) longer than the mean dwell time for glances at lane use markings on approach. Additionally, drivers glanced at lane use markings in the approach 123 times compared to just 30 glances at lane control signs in the approach. The larger number of glances made toward lane use markings in the approach may be partially because lane use markings are in the lane, where they largely overlap with a forward-looking driver's gaze.

Although participant responses to the questionnaire indicated they feel signs and markings are both important for navigating through a roundabout (Appendix C), the eye glance data suggests that drivers are more likely to look for guidance from markings on the pavement than at signs, and that they require less time per glance to do so. This seems to be the case regardless of where the driver is in the roundabout. In the approach, drivers glanced most often at lane use markings to determine which lane they should be in. In the entrance, drivers glanced most often at the outer circulatory roadway lane striping to know where to stop before entering, and in the circle, drivers glanced most often at the center circulatory roadway lane striping for guidance through the roundabouts. However, this result might have been different if the roundabouts in Carmel, IN had lane use markings in the circulatory roadway like those in Hilliard, OH.

One caveat to consider, however, is that all of the data collection for this study occurred during daylight hours and in clear weather. It is possible that a different pattern would emerge at night, when signs appear brighter in a driver's headlamps, or when the pavement is wet and markings become more difficult to see. Additionally, data collection also occurred in two locations where there are a large number of roundabout intersections, and all participants indicated that they were comfortable driving through roundabouts (Appendix C). Drivers who are inexperienced with roundabouts may have different glance patterns.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This research included a video-based erratic maneuver study to examine the effect of roundabout signing and marking on erratic maneuvers in a large sample of study locations, and an eye-tracker study to examine drivers' eye glance behavior in roundabouts.

The video-based study found that some pavement marking applications appear to result in a greater likelihood of erratic maneuvers. The two most dominant contributing factors appear to be (1) inconsistencies between lane use markings on the approach and those within the circulatory roadway, and (2) insufficient channelization for drivers when being shifted from the inside lane to the outside lane to exit. Another contributing factor to erratic maneuvers, but of lesser consequence, appears to be a discrepancy in lane alignment from the entry lane to the receiving circulating lane.

Both of these dominant contributing factors identified above are related in that they are products of lane configurations involving exclusive movements rather than default movements that would be in place without any special lane designations (e.g., left-turn-only versus shared left-through). It appears prudent to be judicious in the design process when identifying the need for exclusive lanes and to be cautious when relying on signing and striping alone to convey the intended paths for these movements. It also appears prudent to conduct post-construction field reviews for sites with these exclusive movements to determine whether erratic maneuvers are occurring and whether any field adjustments to the signing, striping, and/or geometry may be beneficial. This research did not look into the extent to which these erratic maneuvers are significantly different from what may be experienced at other intersection forms with similar exclusive lanes, so it is not possible on the basis of this research alone to conclude that the observed phenomena are unique to roundabouts or that techniques suggested here to address these issues may also be beneficial at other intersection forms. Further experimentation and research in this area is recommended.

The eye tracker study showed that when navigating roundabouts during daylight hours and clear weather conditions, drivers were more likely to glance at markings than at signs. Specifically, drivers made approximately three times more glances toward markings than toward signs, suggesting that drivers rely more heavily on pavement markings than signs to navigate through roundabouts. When similar information is presented by a sign and a marking (i.e., lane control sign and lane use marking), drivers glance toward the marking more often, and spend less time per glance. The eye tracker study showed that, when the vehicle was approaching the roundabout, drivers glanced at lane use pavement markings four times as much as at lane control signs, and those glances were on average 140 ms shorter, suggesting potentially a more intuitive understanding.

The overall conclusion that can be drawn from these two studies is that correct pavement markings appear to be the most important traffic control devices to minimize erratic maneuvers, and thus conflicts and crashes. Drivers appear to focus considerably more attention on the markings than on signs, thus making communication of lane use and correct alignment via pavement marking beneficial. The study does not suggest that pavement markings should replace signing, but it is important that roundabout approaches and the circulatory roadway be equipped with at least some lane use pavement markings that are correct for the lane configuration of the intersection. As noted above, the video-based erratic maneuver study suggests that the absence or incorrect use of lane use pavement markings on the approach is one of the contributing factors to erratic maneuvers within the roundabout as drivers make last-minute lane changes.

RECOMMENDATIONS FOR FUTURE RESEARCH

In addition to the recommended research and experimentation associated with exclusive lanes as described above, a recommendation for future research is to conduct a targeted investigation on the effect of various marking patterns within the circulatory roadway (and no striping) on driver behavior. A particular focus should be a comparison of various spiraling patterns and physical extensions of the truck apron to determine their effectiveness with respect to vehicle path alignment through the roundabout. Since field studies are confounded by differences in driver culture and geometry as was evident in the video-based conflict study performed here, a before-after study at selected locations that can reproduce the physical variations in these spiraling patterns across a range of observed driver patterns may be the preferred research approach.

APPENDIX A. DETAILED SITE INVENTORY AND VIDEO-BASED CONFLICT STUDY

This section presents an individual evaluation for each roundabout. Each of the erratic maneuvers logged are provided in a table for each roundabout for the studied legs. For the erratic maneuvers of interest in this study (approach lane change, approach turn, circulating straddle, circulating lane change, and circulating turn), the percentile rankings are provided if the particular value exceeds the 75^{th} percentile among the sites studied (excluding the Hilliard sites, which were analyzed separately).

Avon Rd./Benchmark Rd., Avon, CO

This roundabout, completed in 1997, is illustrated in figure 20. Observed volumes and erratic maneuvers are provided in table 8.

Figure 20. Photo. Avon Rd./Benchmark Rd., Avon, CO (Source: Google Maps 2015)

Table 8. Observed Volumes and Erratic Maneuvers at Avon Rd./Benchmark Rd., Avon, CO

Observed Volume or Erratic Maneuver	South Leg (Avon-6)	North Leg (Avon-2)
Approach volume (veh/h)	557	627
Circulating volume (veh/h)	327	342
Approach lane change (percent)	5.4 (84th percentile)	4.0 (76th percentile)
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	1.5	10.2 (95th percentile)
Circulating lane change (percent)	12.5 (97th percentile)	0.0
Circulating turn (percent)	2.1	1.0
Circulating yield (percent)	0.3	0.0

Both the north and south legs have a standard left-through, through-right lane configuration, although the left-turn arrow is omitted from the pavement markings in the left lane on the approach. However, lane changes and lane straddles within the circulatory roadway are likely caused by the circulatory roadway lane configuration, which designates the inside circulating lane as left-turn only (a trap lane). No spiral markings or physical channelization is provided to guide the northbound and southbound left-turn movements into the outside circulating lane to avoid this trap. In addition, the westbound left entry lane is designated as a through movement on the entry but is actually a left-turn only lane once inside the roundabout. These alignment and lane designation inconsistencies are the likely causes of the observed erratic maneuvers.

Avon Rd./Beaver Creek Blvd., Avon, CO

This roundabout, completed in 1997, is illustrated in figure 21. Observed volumes and erratic maneuvers are provided in table 9.

Figure 21. Photo. Avon Rd./Beaver Creek Blvd., Avon, CO (Source: Google Maps 2015)

Table 9. Observed Volumes and Erratic Maneuvers at Avon Rd./Beaver Creek Blvd., Avon, CO

Observed Volume or Erratic Maneuver	South Leg (Avon-1)	East Leg (Avon-5)
Approach volume (veh/h)	493	416
Circulating volume (veh/h)	496	966
Approach lane change (percent)	4.1 (79th percentile)	11.5 (97th percentile)
Approach turn (percent)	0.0	6.0 (100th percentile)
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	3.4	0.5
Circulating lane change (percent)	1.0	5.0
Circulating turn (percent)	1.2 (76th percentile)	0.9
Circulating yield (percent)	0.0	0.1

Both the south and east legs are designated with lane-use markings on the approach as having two through lanes and a right-turn-only lane. However, for consistency with the single exit lane on the west leg and the striping within the roundabout, the east leg should be designated as left-turn-only, through-only, right-turn-only as soon as it completes its flaring from one to three lanes. Likewise, the south leg should be designated left-through, through-only, and right-turn only so that left-turning vehicles know to use the left lane. In both cases the left-turn arrow is omitted from the pavement markings in the left lane on the approach. No spiral markings or physical channelization is provided to guide the northbound and southbound left-turn movements into the outside circulating lane.

Geometrics may also be playing a factor. The elliptical shape of the roundabout creates a long section of circulatory roadway between the east entry and north exit, which makes it particularly difficult for drivers on the east leg to align properly with the circulatory roadway. The relatively narrow width of the circulatory roadway between these legs also makes it less comfortable for drivers to maintain lane position. The entry lanes on the south leg also misalign with the receiving circulating lanes.

Avon Rd./US 6, Avon, CO

This roundabout, completed in 1997, is illustrated in figure 22. Observed volumes and erratic maneuvers are provided in table 10.

Figure 22. Photo. Avon Rd./US 6, Avon, CO (Source: Google Maps 2015)

Table 10. Observed Volumes and Erratic Maneuvers at Avon Rd./US 6, Avon, CO

Observed Volume or Erratic Maneuver	West Leg (Avon-3)	North Leg (Avon-4)
Approach volume (veh/h)	410	667
Circulating volume (veh/h)	529	311
Approach lane change (percent)	4.6 (82nd percentile)	2.2
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	0.9	14.8 (100th percentile)
Circulating lane change (percent)	14.0 (100th percentile)	5.8
Circulating turn (percent)	2.1 (79th percentile)	0.0
Circulating yield (percent)	0.0	0.3

Both the north and west legs have two-lane entries with the same lane use arrows: through and through-right. In both cases the left-turn arrow is omitted from the pavement markings in the left lane on the approach. However, the east and west legs are actually intended to have a left-turn only lane based on the single-lane exit on the opposite leg and the associated circulatory roadway pavement markings. This conflict shows in the high percentage of circulating straddles and circulating lane changes for the north leg, which reflects the similar challenge for drivers traveling as through movements from east to west. These lane designation inconsistencies are the likely causes of the observed erratic maneuvers.

Edwards Access Rd./Beard Creek Rd./I-70 WB Ramps, Edwards, CO

This roundabout, completed in 2010, is illustrated in figure 23. Observed volumes and erratic maneuvers are provided in table 11.

Figure 23. Photo. Edwards Access Rd./Beard Creek Rd./I-70 WB Ramps, Edwards, CO (Source: Google Earth 2011)

Table 11. Observed Volumes and Erratic Maneuvers at Edwards Access Rd./Beard Creek Rd./I-70 WB Ramps, Edwards, CO

Observed Volume or Erratic Maneuver	North Leg (Edwards-1)	East Leg (Edwards-2)
Approach volume (veh/h)	692	217
Circulating volume (veh/h)	224	417
Approach lane change (percent)	2.6	0.9
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	1.8	0.0
Circulating lane change (percent)	0.0	0.0
Circulating turn (percent)	0.0	0.2
Circulating yield (percent)	0.4	0.0

Erratic maneuvers are notably low at this site. The geometry to guide northbound left turns into the outer lane appears smooth, and this is likely a cause of the low percentage of circulating straddles and lane changes at the north leg.

Edwards Access Rd./I-70 EB Ramps, Edwards, CO

This roundabout, completed in 2010, is illustrated in figure 24. Observed volumes and erratic maneuvers are provided in table 12.

Figure 24. Photo. Edwards Access Rd./I-70 EB Ramps, Edwards, CO (Source: Google Earth 2011)

Table 12. Observed Volumes and Erratic Maneuvers at Edwards Access Rd. /I-70 EB Ramps, Edwards, CO

Observed Volume or Erratic Maneuver	West Leg (Edwards-4)
Approach volume (veh/h)	657
Circulating volume (veh/h)	397
Approach lane change (percent)	0.8
Approach turn (percent)	0.0
Approach yield (percent)	0.0
Circulating straddle (percent)	2.5
Circulating lane change (percent)	3.0
Circulating turn (percent)	0.3
Circulating yield (percent)	0.0

Erratic maneuvers are relatively low at this site. The straddles and lane changes may be due to positioning for downstream turning movements at the next roundabout, whose entrance line is only 230 feet downstream.

Edwards Access Rd./Miller Ranch Rd., Edwards, CO

This roundabout, completed in 2010, is illustrated in figure 25. Observed volumes and erratic maneuvers are provided in table 13.

Figure 25. Photo. Edwards Access Rd./Miller Ranch Rd., Edwards, CO (Source: Google Earth 2011)

Table 13. Observed Volumes and Erratic Maneuvers at Edwards Access Rd./Miller Ranch Rd., Edwards, CO

Observed Volume or Erratic Maneuver	South Leg (Edwards-5)	East Leg (Edwards-3)
Approach volume (veh/h)	245	172
Circulating volume (veh/h)	791	592
Approach lane change (percent)	9.0 (95^{th} percentile)	1.7
Approach turn (percent)	0.0	3.5 (97^{th} percentile)
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	3.0	0.0
Circulating lane change (percent)	4.9	1.5
Circulating turn (percent)	0.0	0.3
Circulating yield (percent)	0.0	0.0

The south leg experiences a high percentage of lane changes on the approach and a moderate percentage of circulating straddles and lane changes for the conflicting circulating movement. Each appears to be the outcome of drivers taking a fastest path with little potential conflict due to arriving as a single stream of vehicles. The conflicting circulating movement, occupied primarily by southbound left turns, is a wide single lane.

S. Golden Rd./Johnson St./16th Ave, Golden, CO

This roundabout, completed in 1998, is illustrated in figure 26. Observed volumes and erratic maneuvers are provided in table 14.

Figure 26. Photo. S. Golden Rd./Johnson St./16th Ave., Golden, CO (Source: Google Earth 2014)

Table 14. Observed Volumes and Erratic Maneuvers at S. Golden Rd./Johnson St./16th Ave., Golden, CO

Observed Volume or Erratic Maneuver	Southeast Leg (Golden-1)
Approach volume (veh/h)	543
Circulating volume (veh/h)	334
Approach lane change (percent)	0.0
Approach turn (percent)	0.0
Approach yield (percent)	0.0
Circulating straddle (percent)	2.1
Circulating lane change (percent)	1.8
Circulating turn (percent)	12.9 (100th percentile)
Circulating yield (percent)	0.0

The erratic maneuver of particular note at this site is the circulating turn maneuver in front of the southeast leg. Drivers making the southeast-bound left-turn movement from South Golden Road onto 16th Avenue who start (correctly) in the left entry lane to make a left-turn movement must then change lanes to exit onto 16th Avenue. To avoid changing lanes within the circulatory roadway, the drivers would need to incorrectly begin the left-turn movement from the right entry lane, which conflicts with drivers making legal through movements from both entry lanes. This inconsistency between approach lane designation and circulating lane markings is the likely causes of the observed erratic maneuvers.

Hazel Dell Pkwy./126th St., Carmel, IN

This roundabout, completed in 1998, is illustrated in figure 27. Observed volumes and erratic maneuvers are provided in table 15.

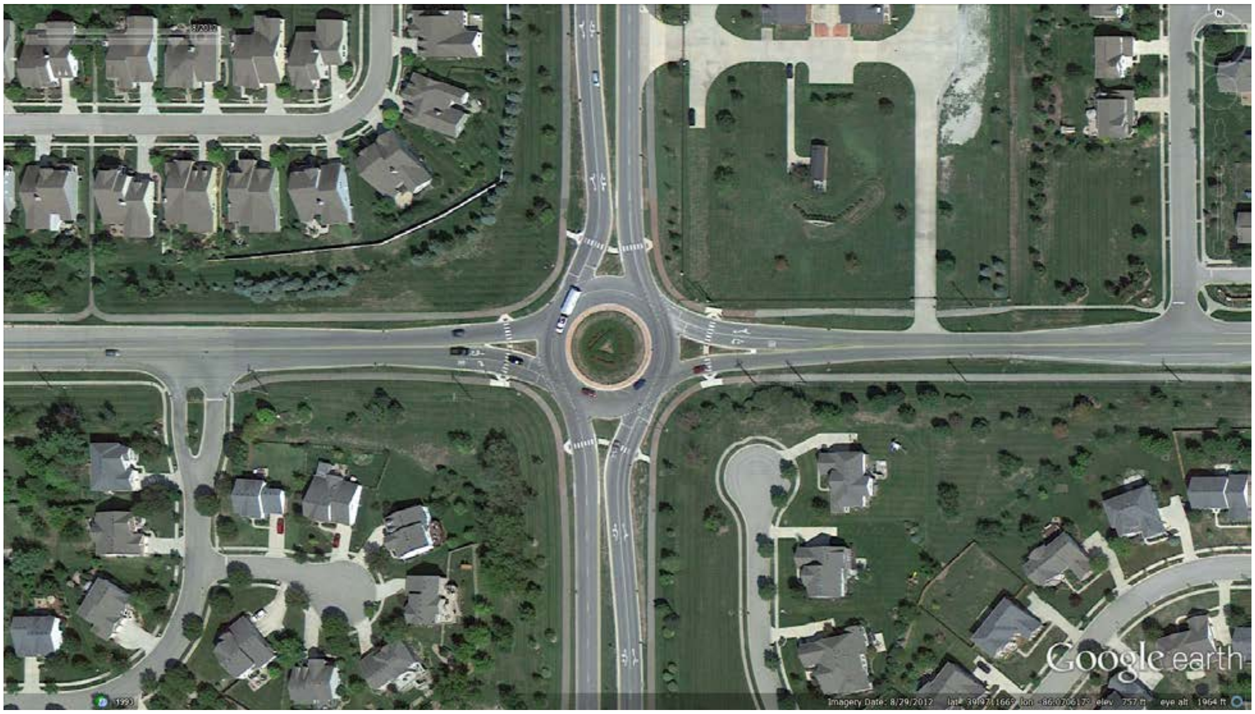

Figure 27. Photo. Hazel Dell Pkwy./126th St., Carmel, IN (Source: Google Earth 2012)

Table 15. Observed Volumes and Erratic Maneuvers at Hazel Dell Pkwy./126th St., Carmel, IN

Observed Volume or Erratic Maneuver	East Leg (Carmel-3)	North Leg (Carmel-4)
Approach volume (veh/h)	118	127
Circulating volume (veh/h)	1344	800
Approach lane change (percent)	15.3 (100th percentile)	5.5 (87th percentile)
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	0.1	0.1
Circulating lane change (percent)	0.0	4.8
Circulating turn (percent)	0.1	0.0
Circulating yield (percent)	0.1	0.0

The large number of approach lane changes on the east leg is likely caused by the lane configuration of the entry, which requires drivers to use only the right lane to go through to a single-lane exit on the west leg. These lane changes also appear at a moderate level in the circulating lane changes in front of the north leg. Because the east leg flares from one to two lanes, the lane changes on the approach may be attributable to drivers not perceiving a conflict because the drivers are arriving in a single stream. Another contributing factor may be the use of only one set of lane control signs and lane use pavement markings within 100 ft of the roundabout entry. The relatively high conflicting flow in this location may cause some drivers to queue up side-by-side regardless of destination and then change lanes once in the roundabout; this may explain some of the circulating lane changes.

Illinois St./116th St., Carmel, IN

This roundabout, completed in 2005, is illustrated in figure 28. Observed volumes and erratic maneuvers are provided in table 16.

Figure 28. Photo. Illinois St./116th St., Carmel, IN (Source: Google Earth 2012)

Table 16. Observed Volumes and Erratic Maneuvers at Illinois St./116th St., Carmel, IN

Observed Volume or Erratic Maneuver	East Leg (Carmel-1)	South Leg (Carmel-2)
Approach volume (veh/h)	849	1585
Circulating volume (veh/h)	231	545
Approach lane change (percent)	0.6	2.0
Approach turn (percent)	0.1 (84th percentile)	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	10.5 (97th percentile)	2.2
Circulating lane change (percent)	6.1	0.7
Circulating turn (percent)	0.0	0.4
Circulating yield (percent)	0.0	0.0

The most common erratic maneuvers observed at this site are circulating straddles and lane changes within the circulatory roadway in front of the east leg. The most likely cause of this is the low circulating flow during the observed period. Drivers under these flow conditions likely were not traveling next to other vehicles and thus could straddle or change lanes with little consequence. Another possible cause is geometric. There appears to be a minor amount of path misalignment on the entries and exits that could guide drivers from the right entry lane on the south leg to the left circulating lane and then to the right exiting lane on the north leg.

SR 67/Blacksmith Dr./Kelch Dr., Malta, NY

This roundabout, completed in 2006, is illustrated in figure 29. Observed volumes and erratic maneuvers are provided in table 17.

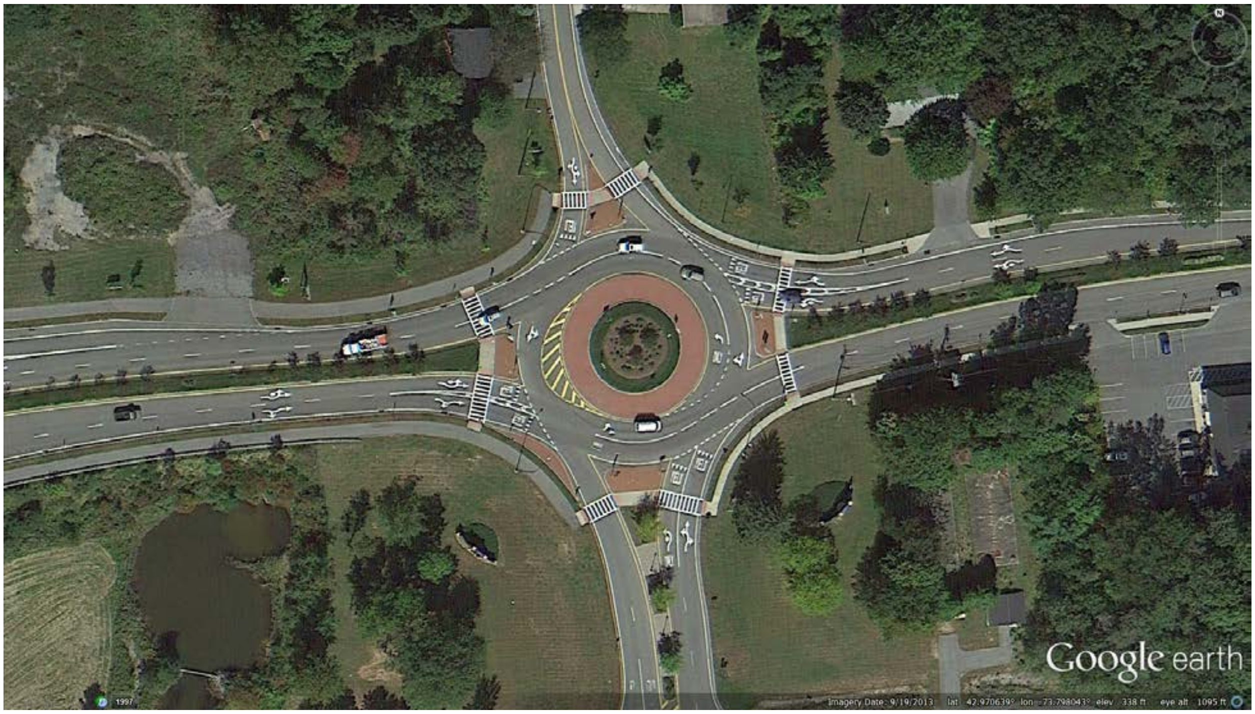

Figure 29. Photo. SR 67/Blacksmith Dr./Kelch Dr., Malta, NY (Source: Google Earth 2013)

Table 17. Observed Volumes and Erratic Maneuvers at SR 67/Blacksmith Dr./Kelch Dr., Malta, NY

Observed Volume or Erratic Maneuver	East Leg (Malta-10)	West Leg (Malta-09)
Approach volume (veh/h)	495	541
Circulating volume (veh/h)	106	53
Approach lane change (percent)	7.1 (92nd percentile)	1.5
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.1	0.1
Circulating straddle (percent)	8.5 (89th percentile)	6.4 (82nd percentile)
Circulating lane change (percent)	10.4 (89th percentile)	11.0 (92nd percentile)
Circulating turn (percent)	0.9	7.5 (95th percentile)
Circulating yield (percent)	0.0	0.0

This experiences a high percentage of circulating straddles and lane changes in front of the east and west legs, as well as a relatively high percentage of approach lane changes on the east leg. This roundabout is located immediately east of the SR 67/I-87 interchange, and drivers intending to go north on I-87 would need to be in the right lane to use the on-ramp. If these drivers started their left turn at SR 67/Kelch Drive from the left lane, they would need to change lanes somewhere to position themselves correctly. There were also some observations of drivers entering from the south in the left lane and exiting to the north, changing lanes to exit (recorded as a circulating lane change in front of the east leg).

For the west leg, the observed circulating volumes were relatively low. Some drivers making a westbound left turn turned from the outside lane, and others straddled the hatched spiral area next to the truck apron. These conflicts may be the product of some confusion about the spiral marking.

SR 67/I-87 SB Ramps, Malta, NY

This roundabout, completed in 2006, is illustrated in figure 30. Observed volumes and erratic maneuvers are provided in table 18.

Figure 30. Photo. SR 67/I-87 SB Ramps, Malta, NY (Source: Google Earth 2013)

Table 18. Observed Volumes and Erratic Maneuvers at SR 67/I-87 SB Ramps, Malta, NY

Observed Volume or Erratic Maneuver	East Leg (Malta-02)	West Leg (Malta-03)
Approach volume (veh/h)	950	393
Circulating volume (veh/h)	34	389
Approach lane change (percent)	0.6	2.3
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.3	0.5
Circulating straddle (percent)	0.0	7.0 (84^{th} percentile)
Circulating lane change (percent)	0.0	8.2 (79^{th} percentile)
Circulating turn (percent)	0.0	0.0
Circulating yield (percent)	0.0	0.0

The most common erratic maneuvers at this location are circulating straddles and lane changes in front of the west leg. These are primarily caused by westbound drivers intending to turn left onto the on-ramp, hugging the truck apron instead of following the spiral striping, and then either straddling the spiral striping or being forced to change lanes to exit.

SR 67/I-87 NB Ramps, Malta, NY

This roundabout, completed in 2006, is illustrated in figure 31. Observed volumes and erratic maneuvers are provided in table 19.

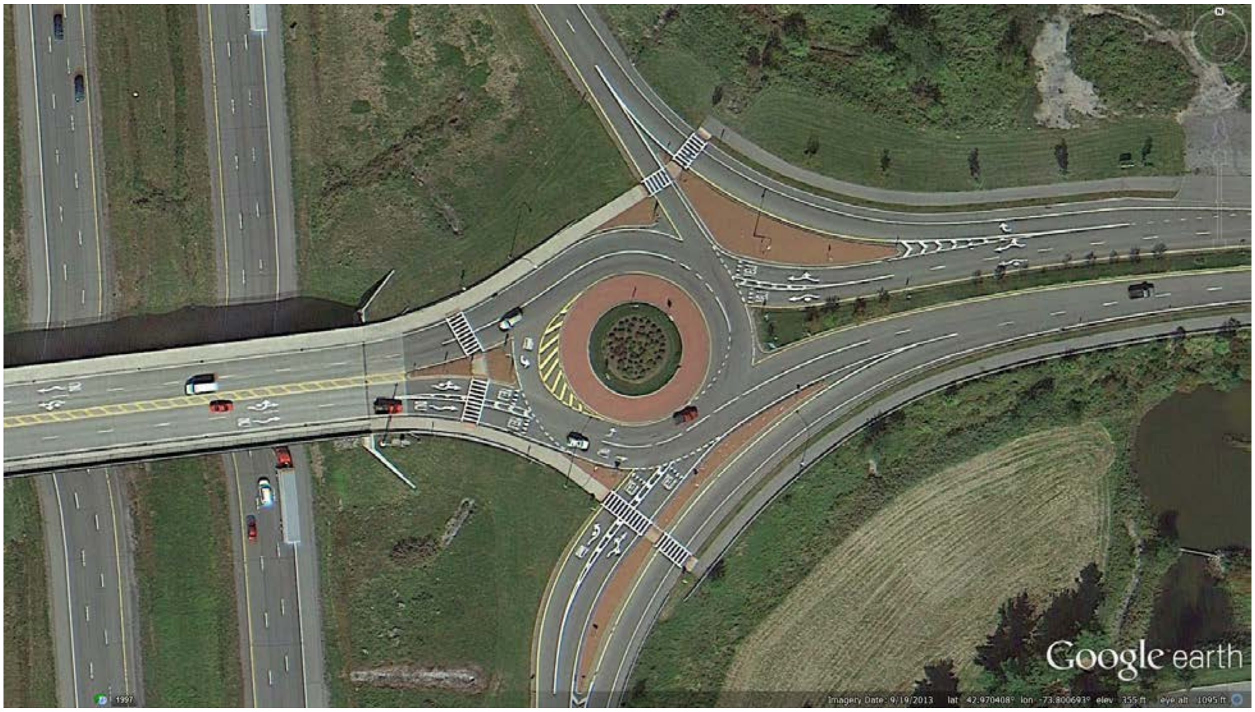

Figure 31. Photo. SR 67/I-87 NB Ramps, Malta, NY (Source: Google Earth 2013)

Table 19. Observed Volumes and Erratic Maneuvers at SR 67/I-87 NB Ramps, Malta, NY

Observed Volume or Erratic Maneuver	East Leg (Malta-05)	West Leg (Malta-04)
Approach volume (veh/h)	350	703
Circulating volume (veh/h)	859	47
Approach lane change (percent)	2.9	1.4
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.4	0.5
Circulating straddle (percent)	5.0 (76^{th} percentile)	0.0
Circulating lane change (percent)	8.0 (76^{th} percentile)	9.0 (84^{th} percentile)
Circulating turn (percent)	0.0	8.0 (97^{th} percentile)
Circulating yield (percent)	0.0	0.0

The geometry here is similar to that at SR 67/I-87 SB Ramps, and as a result the pattern of erratic maneuvers is similar. The most common erratic maneuvers are primarily caused by drivers intending to turn left onto the on-ramp or making a U-turn in front of the west leg, hugging the truck apron instead of following the spiral striping, and then either straddling the spiral striping or being forced to change lanes to exit.

SR 67/US 9, Malta, NY

This roundabout, completed in 2006, is illustrated in figure 32. Observed volumes and erratic maneuvers are provided in table 20.

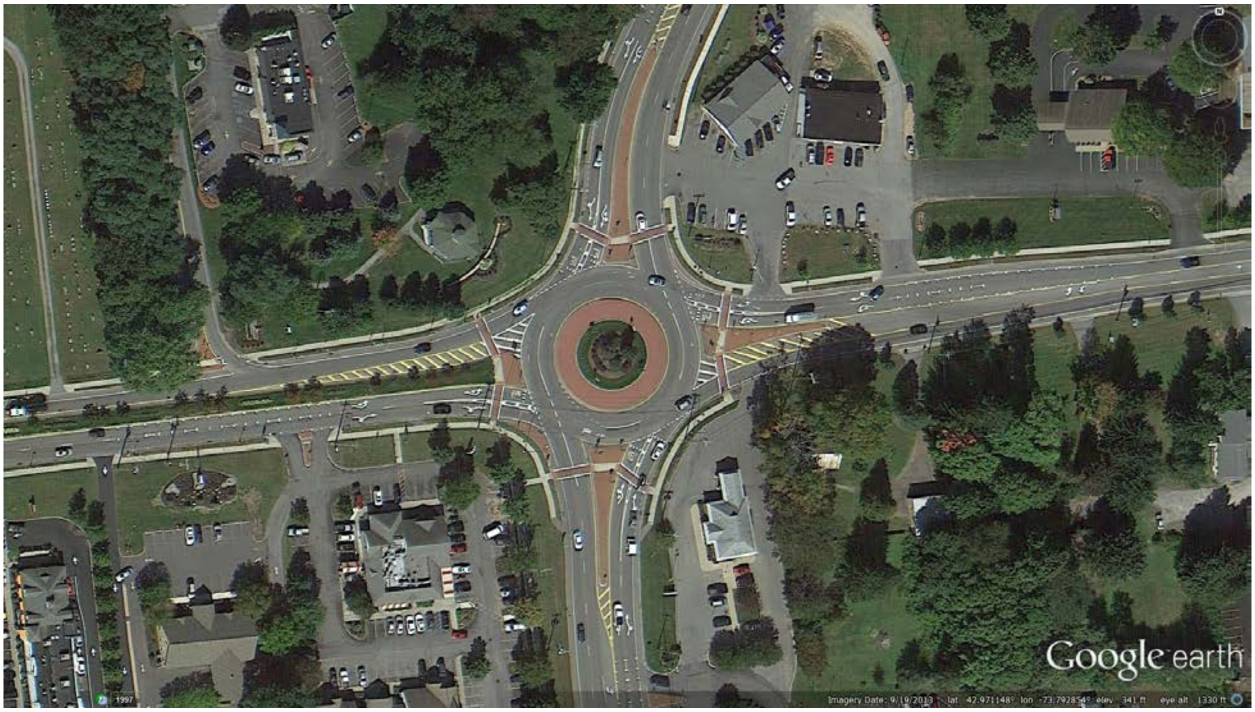

Figure 32. Photo. SR 67/US 9, Malta, NY (Source: Google Earth 2013)

Table 20. Observed Volumes and Erratic Maneuvers at SR 67/US 9, Malta, NY

Observed Volume or Erratic Maneuver	East Leg (Malta-06)	West Leg (Malta-01)
Approach volume (veh/h)	343	682
Circulating volume (veh/h)	709	496
Approach lane change (percent)	0.9	0.7
Approach turn (percent)	0.0	0.1 (89^{th} percentile)
Approach yield (percent)	0.3	0.2
Circulating straddle (percent)	2.0	2.8
Circulating lane change (percent)	6.0	4.4
Circulating turn (percent)	3.0 (87^{th} percentile)	0.8
Circulating yield (percent)	0.0	0.0

This roundabout experienced relatively few erratic maneuvers, with the most common being circulating lane changes in front of the east leg. The circulating turn erratic maneuvers in front of the east leg are likely due to the westbound left-turn-only lane that requires northbound left turns to shift to the outside circulating lane to exit to the west.

SR 67/State Farm Blvd., Malta, NY

This roundabout, completed in 2006, is illustrated in figure 33. Observed volumes and erratic maneuvers are provided in table 21.

Figure 33. Photo. SR 67/State Farm Blvd., Malta, NY (Source: Google Earth 2013)

Table 21. Observed Volumes and Erratic Maneuvers at SR 67/State Farm Blvd., Malta, NY

Observed Volume or Erratic Maneuver	East Leg (Malta-07)	West Leg (Malta-08)
Approach volume (veh/h)	682	602
Circulating volume (veh/h)	73	127
Approach lane change (percent)	2.1	6.0 (89^{th} percentile)
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.4	0.4
Circulating straddle (percent)	0.0	7.0 (84^{th} percentile)
Circulating lane change (percent)	0.0	12.0 (95^{th} percentile)
Circulating turn (percent)	0.0	0.0
Circulating yield (percent)	0.0	0.0

This roundabout experienced a relatively high percentage of approach lane changes on the west leg, as well as a high percentage of circulating straddles and lane changes in front of the west leg. The circulating erratic maneuvers appear to be caused by (1) drivers incorrectly making a through movement in the southbound direction from the left lane and (2) drivers making a westbound left turn and not picking up on the spiral striping that guides them to the outside circulating lane. The likely cause for the approach lane changes on the west leg is not readily apparent.

14th Ave./Jefferson St., Olympia, WA

This roundabout, completed in 2010, is illustrated in figure 34. Observed volumes and erratic maneuvers are provided in table 22.

Figure 34. Photo. 14th Ave./Jefferson St., Olympia, WA (Source: Google Earth 2013)

Table 22. Observed Volumes and Erratic Maneuvers at 14th Ave./Jefferson St., Olympia, WA

Observed Volume or Erratic Maneuver	North Leg (Olympia-2)	South Leg (Olympia-4)
Approach volume (veh/h)	642	209
Circulating volume (veh/h)	704	718
Approach lane change (percent)	1.7	1.0
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	9.2 (92nd percentile)	0.0
Circulating lane change (percent)	3.8	0.0
Circulating turn (percent)	0.1	0.0
Circulating yield (percent)	0.1	0.0

The only erratic maneuver of significance at this roundabout are the circulating lane straddles in front of the north leg. The likely cause of these lane straddles is a slight geometric misalignment of the east leg entry with its receiving section of circulatory roadway in front of the north leg. The right entry lane aims partially into the left circulating lane.

4^{th} Ave./Olympic Way, Olympia, WA

This roundabout, completed in 2004, is illustrated in figure 35. Observed volumes and erratic maneuvers are provided in table 23.

Figure 35. Photo. 4th Ave./Olympic Way, Olympia, WA (Source: Google Earth 2013)

Table 23. Observed Volumes and Erratic Maneuvers at 4^{th} Ave./Olympic Way, Olympia, WA

Observed Volume or Erratic Maneuver	South Leg (Olympia-1)	East Leg (Olympia-3)
Approach volume (veh/h)	532	1078
Circulating volume (veh/h)	812	538
Approach lane change (percent)	3.9	1.0
Approach turn (percent)	0.0	0.1 (82^{nd} percentile)
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	0.0	0.0
Circulating lane change (percent)	0.0	4.5
Circulating turn (percent)	0.1	0.4
Circulating yield (percent)	0.0	0.0

The most significant erratic maneuver observed at this roundabout are the circulating lane changes in front of the east leg. The likely cause of these lane straddles is the long section of circulatory roadway between the east and south legs, which is caused by the skew of the intersection, and the relatively small exit radius leading to the north exit.

Borgen Blvd./51st Ave. NW, Gig Harbor, WA

This roundabout, completed in 2002, is illustrated in figure 36. Observed volumes and erratic maneuvers are provided in table 24.

Figure 36. Photo. Borgen Blvd./51st Ave. NW, Gig Harbor, WA (Source: Google Earth 2015)

Table 24. Observed Volumes and Erratic Maneuvers at Borgen Blvd./51st Ave. NW, Gig Harbor, WA

Observed Volume or Erratic Maneuver	East Leg (Gig Harbor-2)
Approach volume (veh/h)	1002
Circulating volume (veh/h)	229
Approach lane change (percent)	1.2
Approach turn (percent)	0.0
Approach yield (percent)	0.0
Circulating straddle (percent)	6.0 (79th percentile)
Circulating lane change (percent)	10.0 (87th percentile)
Circulating turn (percent)	3.6 (89th percentile)
Circulating yield (percent)	0.0

The most significant erratic maneuvers observed at this roundabout are the circulating straddles, lane changes, and turns in front of the east leg. These are caused primarily by the spiraling alignment of the circulatory roadway in front of the east leg. Drivers have worn off the spiral pavement markings next to the truck apron and then when exiting to the north, they cross the circulating lane striping in front of the north leg that is receiving westbound through movements.

Harbor Hill Dr./Development Entrance, Gig Harbor, WA

This roundabout, completed in 2008, is illustrated in figure 37. Observed volumes and erratic maneuvers are provided in table 25.

Figure 37. Photo. Harbor Hill Dr./Development Entrance, Gig Harbor, WA (Source: Google Earth 2015)

Table 25. Observed Volumes and Erratic Maneuvers at Harbor Hill Dr./Development Entrance, Gig Harbor, WA

Observed Volume or Erratic Maneuver	North Leg (Gig Harbor-1)
Approach volume (veh/h)	318
Circulating volume (veh/h)	69
Approach lane change (percent)	2.5
Approach turn (percent)	0.0
Approach yield (percent)	0.0
Circulating straddle (percent)	0.0
Circulating lane change (percent)	0.0
Circulating turn (percent)	0.0
Circulating yield (percent)	0.0

Few significant erratic maneuvers were observed at this roundabout. The approach lane changes were caused by the dedicated right-turn lane.

SR 539/Pole Rd., Lynden (Whatcom County), WA

This roundabout, completed in 2009, is illustrated in figure 38. Observed volumes and erratic maneuvers are provided in table 26.

Figure 38. Photo. SR 539/Pole Rd., Lynden (Whatcom County), WA (Source: Google Earth 2015)

Table 26. Observed Volumes and Erratic Maneuvers at SR 539/Pole Rd., Lynden (Whatcom County), WA

Observed Volume or Erratic Maneuver	North Leg (Lynden-1)	South Leg (Lynden-3)
Approach volume (veh/h)	632	808
Circulating volume (veh/h)	144	26
Approach lane change (percent)	0.6	1.0
Approach turn (percent)	0.2 (92nd percentile)	0.0
Approach yield (percent)	0.0	0.0
Circulating straddle (percent)	0.0	0.0
Circulating lane change (percent)	0.0	0.0
Circulating turn (percent)	2.1 (82nd percentile)	0.0
Circulating yield (percent)	1.4	0.0

Few erratic maneuvers were observed at this roundabout.

SR 539/Ten Mile Rd., Lynden (Whatcom County), WA

This roundabout, completed in 2009, is illustrated in figure 39. Observed volumes and erratic maneuvers are provided in table 27.

Figure 39. Photo. SR 539/Ten Mile Rd., Lynden (Whatcom County), WA (Source: Google Earth 2015)

Table 27. Observed Volumes and Erratic Maneuvers at SR 539/Ten Mile Rd. , Lynden (Whatcom County), WA

Observed Volume or Erratic Maneuver	South Leg (Lynden-4)
Approach volume (veh/h)	688
Circulating volume (veh/h)	47
Approach lane change (percent)	0.0
Approach turn (percent)	0.1 (87th percentile)
Approach yield (percent)	0.0
Circulating straddle (percent)	0.0
Circulating lane change (percent)	0.0
Circulating turn (percent)	4.3 (92nd percentile)
Circulating yield (percent)	0.0

The most significant erratic maneuver observed at this roundabout are the circulating turns in front of the south leg. These are most likely caused by drivers making a southbound left turn by starting from the right entry lane so that they are aligned into the outer circulating lane.

SR 539/Wiser Lake Rd., Lynden (Whatcom County), WA

This roundabout, completed in 2009, is illustrated in figure 40. Observed volumes and erratic maneuvers are provided in table 28.

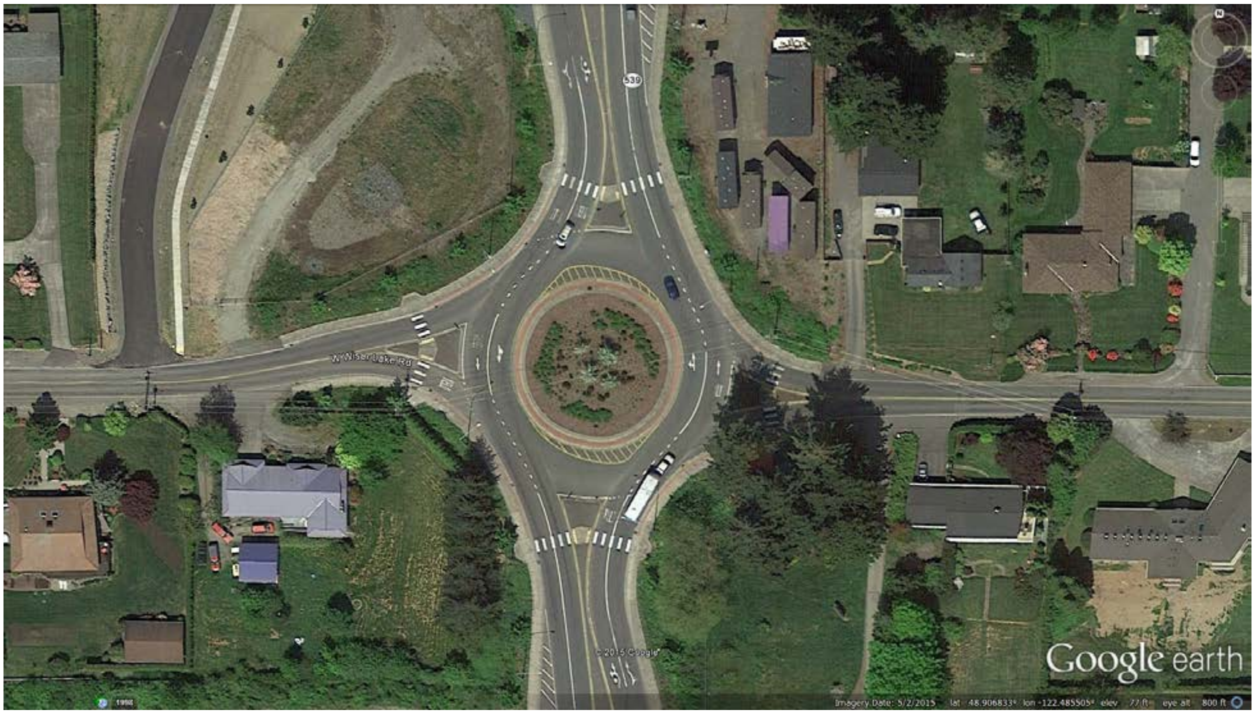

Figure 40. Photo. SR 539/Wiser Lake Rd., Lynden (Whatcom County), WA (Source: Google Earth 2015)

Table 28. Observed Volumes and Erratic Maneuvers at SR 539/Wiser Lake Rd., Lynden, (Whatcom County) WA

Observed Volume or Erratic Maneuver	North Leg (Lynden-2)
Approach volume (veh/h)	613
Circulating volume (veh/h)	160
Approach lane change (percent)	1.0
Approach turn (percent)	0.0
Approach yield (percent)	0.0
Circulating straddle (percent)	0.0
Circulating lane change (percent)	0.0
Circulating turn (percent)	0.0
Circulating yield (percent)	0.0

Very few erratic maneuvers were observed at this roundabout.

Jackson St./Murdock Ave., Oshkosh, WI

This roundabout, completed in 2010, is illustrated in figure 41. Observed volumes and erratic maneuvers are provided in table 29.

Figure 41. Photo. Jackson St./Murdock Ave., Oshkosh, WI (Source: Google Earth 2015)

Table 29. Observed Volumes and Erratic Maneuvers at Jackson St./Murdock Ave., Oshkosh, WI

Observed Volume or Erratic Maneuver	East Leg (Oshkosh-2)	West Leg (Oshkosh-1)
Approach volume (veh/h)	448	602
Circulating volume (veh/h)	593	729
Approach lane change (percent)	1.8	0.0
Approach turn (percent)	0.0	0.0
Approach yield (percent)	0.0	0.2
Circulating straddle (percent)	3.0	0.0
Circulating lane change (percent)	8.2 (79^{th} percentile)	2.4
Circulating turn (percent)	0.0	0.2
Circulating yield (percent)	0.1	0.1

The most significant erratic maneuver observed at this roundabout are the circulating lane changes in front of the east leg. The causes of these lane changes are most likely due to positioning for downstream destinations; the nearest intersections or entrances to left turn pockets are less than 150 ft away from the roundabout.

Main St./Cemetery Rd., Hilliard, OH

This roundabout, completed in 2009, is illustrated in figure 42. Observed volumes and erratic maneuvers are provided in table 30.

Figure 42. Photo. Main St./Cemetery Rd., Hilliard, OH (Source: Google Earth 2014)

Table 30. Observed Volumes and Erratic Maneuvers at Main St./Cemetery Rd., Hilliard, OH

Time Period	Approach Volume (vph)	Approach Lane Change (vph)	Approach Straddle (vph)	Approach Turn (vph)	Approach Yield (vph)	Circulating Volume (vph)	Circulating Lane Change (vph)	Circulating Straddle (vph)	Circulating Turn (vph)	Circulating Yield (vph)
630-730	252	5	0	0	3	160	2	4	0	0
730-830	636	0	0	0	3	296	7	4	0	0
830-930	464	3	1	0	1	400	11	4	1	0
930-1030	276	1	2	2	0	352	6	5	0	0
1030-1130	284	1	1	1	2	392	17	4	0	0
1130-1230	316	2	1	3	3	520	20	4	2	0
1230-1330	368	2	0	0	2	612	10	3	1	0
1330-1430	304	2	0	1	0	496	7	2	0	0
1430-1530	468	0	0	2	2	504	9	1	0	0
1530-1630	356	0	0	0	1	668	5	1	0	0
1630-1730	408	2	0	0	6	780	5	1	2	0
1730-1830	356	1	0	0	3	896	10	1	0	1
1830-1930	356	1	0	1	3	632	14	0	0	0
Total	4,844	20	5	10	29	6,708	123	34	6	1

Main St./Scioto Darby Rd., Hilliard, OH

This roundabout, completed in 2009, is illustrated in figure 43. Observed volumes and erratic maneuvers are provided in table 31.

Figure 43. Photo. Main St./Scioto Darby Rd., Hilliard, OH (Source: Google Earth 2014)

Table 31. Observed Volumes and Erratic Maneuvers at Main St./Scioto Darby Rd., Hilliard, OH

Time Period	Approach Volume (vph)	Approach Lane Change	Approach Straddle	Approach Turn	Approach Yield	Circulating Volume (vph)	Circulating Lane Change	Circulating Straddle	Circulating Turn	Circulating Yield
630-730	88	3	0	0	0	592	4	10	0	0
730-830	144	0	0	0	1	1,240	1	23	0	1
830-930	248	2	2	0	3	808	2	22	0	1
930-1030	92	0	0	0	0	580	6	26	0	0
1030-1130	96	5	0	0	1	600	4	19	0	1
1130-1230	152	0	0	0	2	704	3	20	0	1
1230-1330	208	0	0	0	0	872	1	22	0	0
1330-1430	180	1	0	0	1	764	4	13	0	0
1430-1530	276	2	0	0	1	756	2	11	0	0
1530-1630	376	4	1	0	1	892	4	14	0	0
1630-1730	384	5	0	0	0	816	3	7	0	0
1730-1830	412	2	2	0	1	1,044	8	8	0	0
1830-1930	280	2	0	0	0	1,016	3	11	0	0
Total	2,936	26	5	0	11	10,684	45	206	0	4

APPENDIX B. EYE TRACKER STUDY POST-DRIVE QUESTIONNAIRE

Date:

Time:

Subject Number:

1. How many years have you been driving in the United States? (less than 5 years, between 5 and 10 years, between 10 and 20 years, and more than 20 years)
2. How many hours a day do you drive? (less than an hour, between 1 and 2 hours, more than 2 hours)
3. How many times a week do you drive through a roundabout (or multiple roundabouts)? (less than once a week, between 1 and 555 times a week, more than 5 times a week)
4. Do you drive through a single-lane or a multi-lane roundabout? (single-lane, multi-lane, both)
5. I am comfortable navigating through roundabouts. (strongly disagree, disagree, neutral/don't know, agree, strongly agree)
6. I am comfortable negotiating traffic and choosing my lane at the **entry** of a roundabout. (strongly disagree, disagree, neutral/don't know, agree, strongly agree)
7. I am comfortable negotiating traffic and choosing my lane in the **circulating lanes** of a roundabout. (strongly disagree, disagree, neutral/don't know, agree, strongly agree)
8. I am comfortable negotiating traffic and choosing my lane at the **exit** of a roundabout. (strongly disagree, disagree, neutral/don't know, agree, strongly agree)
9. **Signs** help me navigate as I approach and drive through a roundabout. (strongly disagree, disagree, neutral/don't know, agree, strongly agree)
10. **Pavement markings** help me navigate as I approach and drive through a roundabout. (strongly disagree, disagree, neutral/don't know, agree, strongly agree)
11. Which of the following do you pay more attention to as you approach and drive through the roundabouts? (signs along the way to the roundabout, in circulating lanes, and upon exiting; pavement markings and lane striping on the approach and in the circulating lanes; both; neither; I take a guess or I know my way)

APPENDIX C. EYE TRACKER STUDY QUESTIONNAIRE RESULTS

The results of the eye-tracking study questionnaire are shown in figure 40 through figure 50.

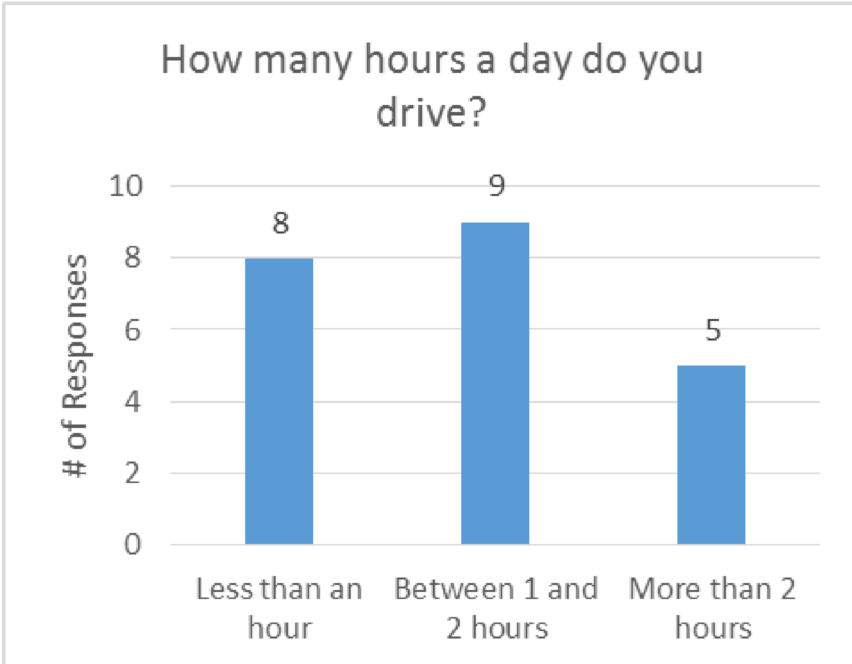

Figure 44. Chart. Questionnaire results for "How many hours a day do you drive?"

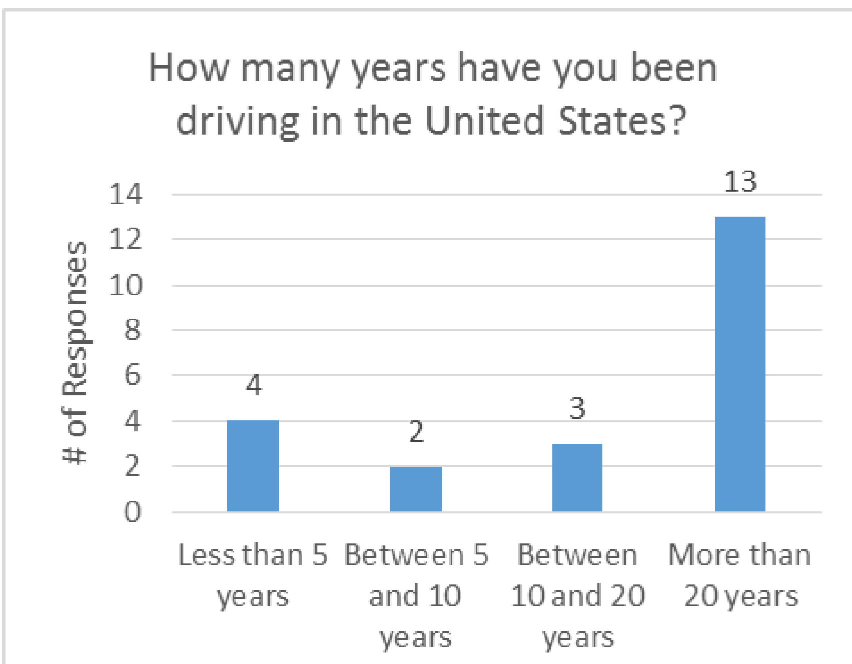

Figure 45. Chart. Questionnaire results for "How many years have you been driving in the United States?"

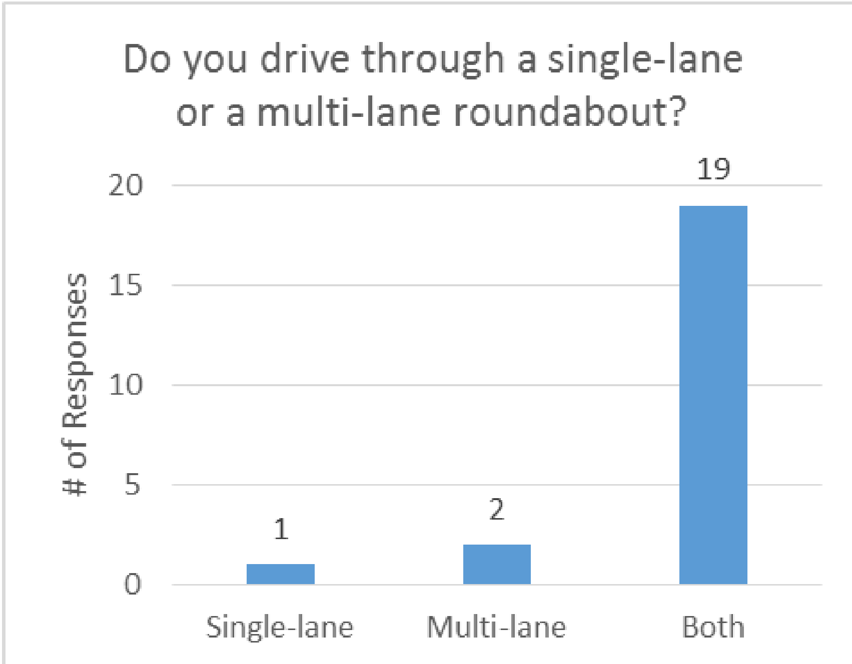

Figure 46. Chart. Questionnaire results for "Do you drive through a single-lane or a multi-lane roundabout?"

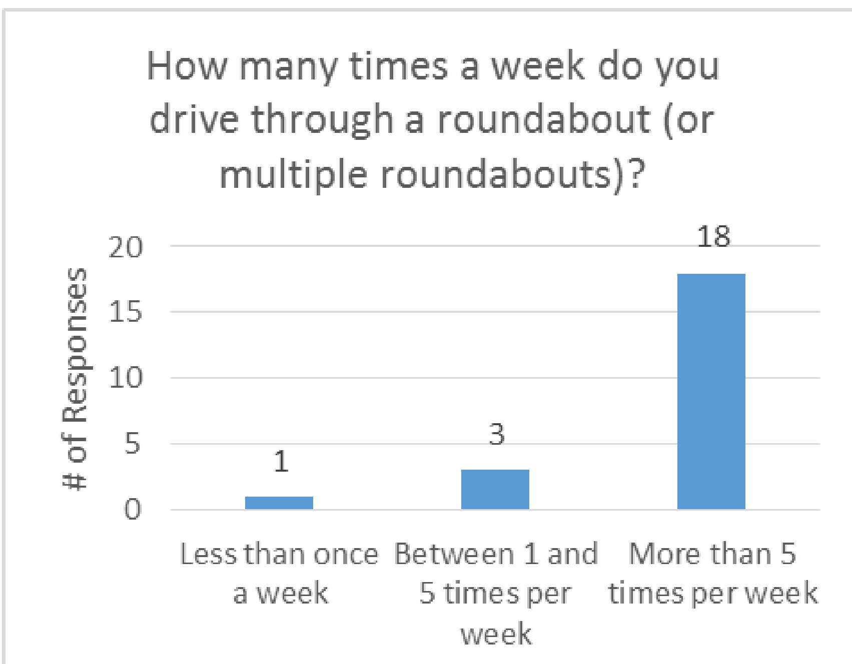

Figure 47. Chart. Questionnaire results for "How many times a week do you drive through a roundabout (or multiple roundabouts)?"

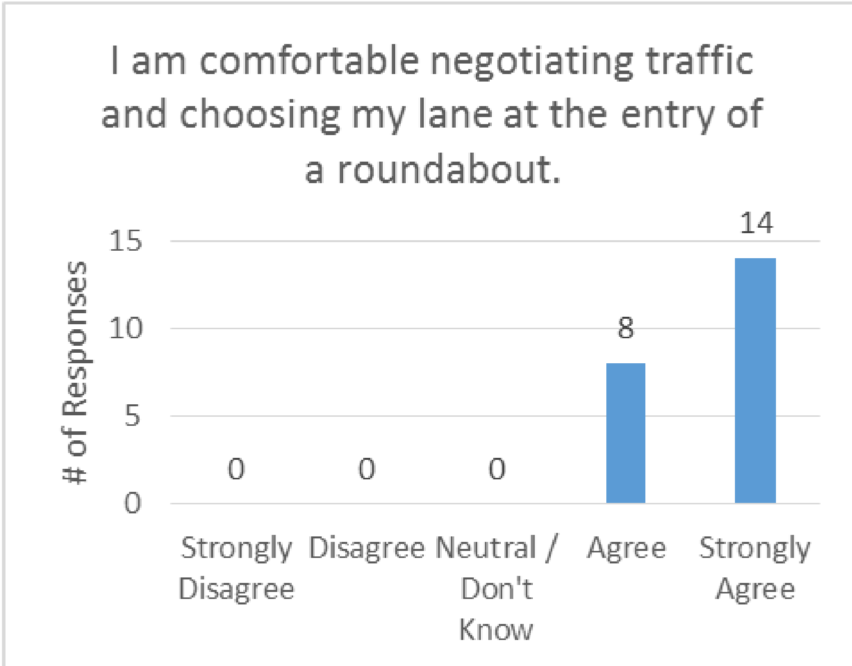

Figure 48. Chart. Questionnaire results for "I am comfortable negotiating traffic and choosing my lane at the entry of a roundabout."

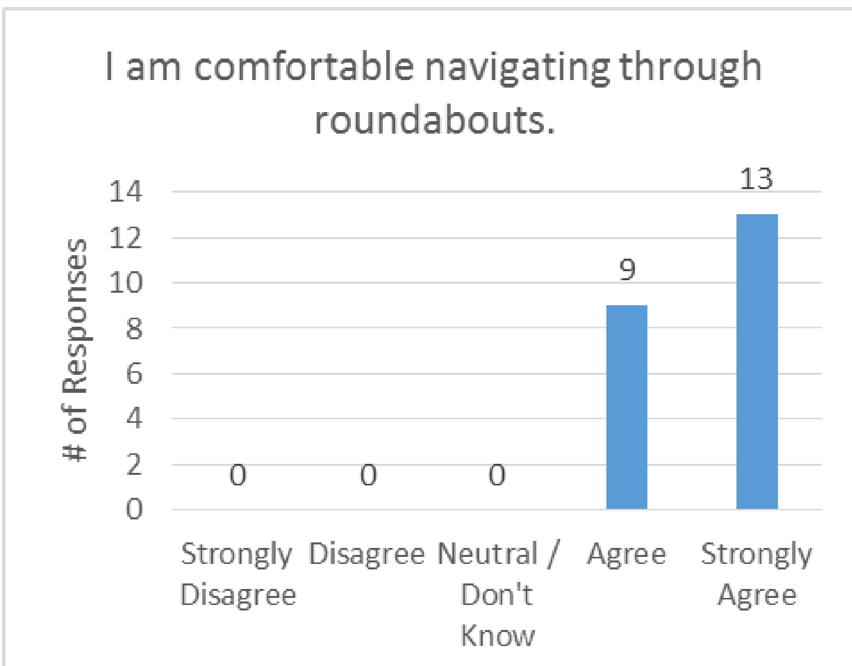

Figure 49. Chart. Questionnaire results for "I am comfortable navigating through roundabouts."

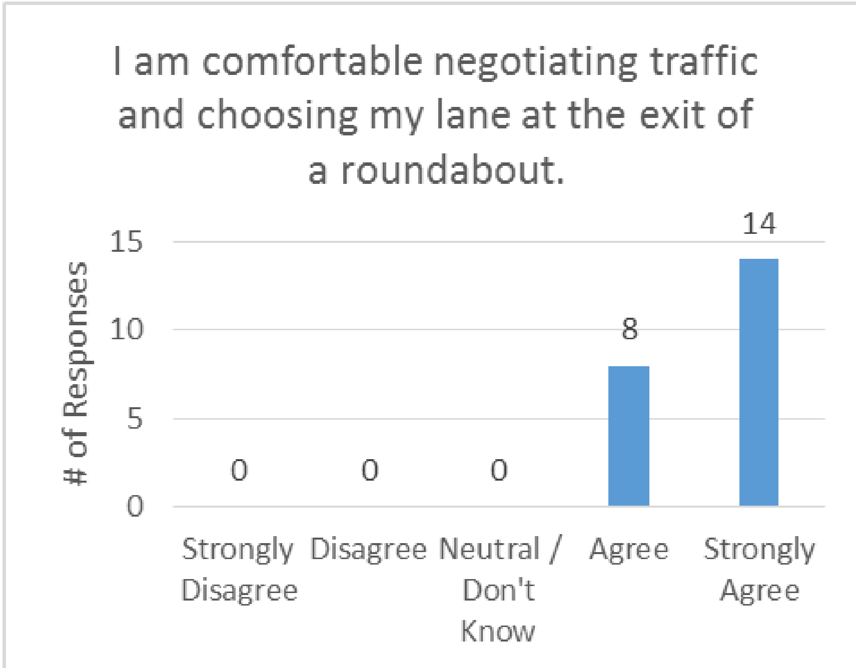

Figure 50. Chart. Questionnaire results for "I am comfortable negotiating and choosing my lane at the exit of a roundabout."

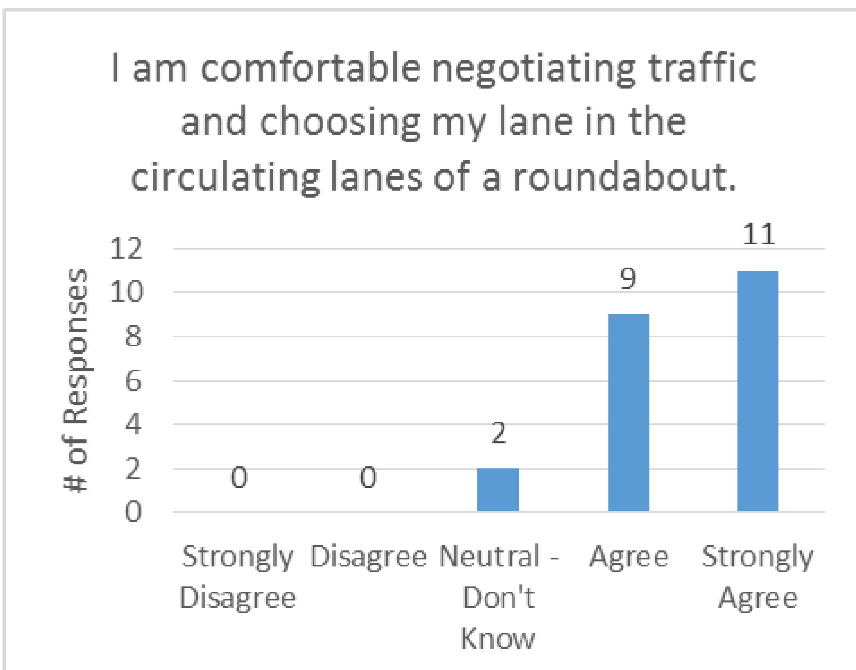

Figure 51. Chart. Questionnaire results for "I am comfortable negotiating and choosing my lane in the circulating lanes of a roundabout."

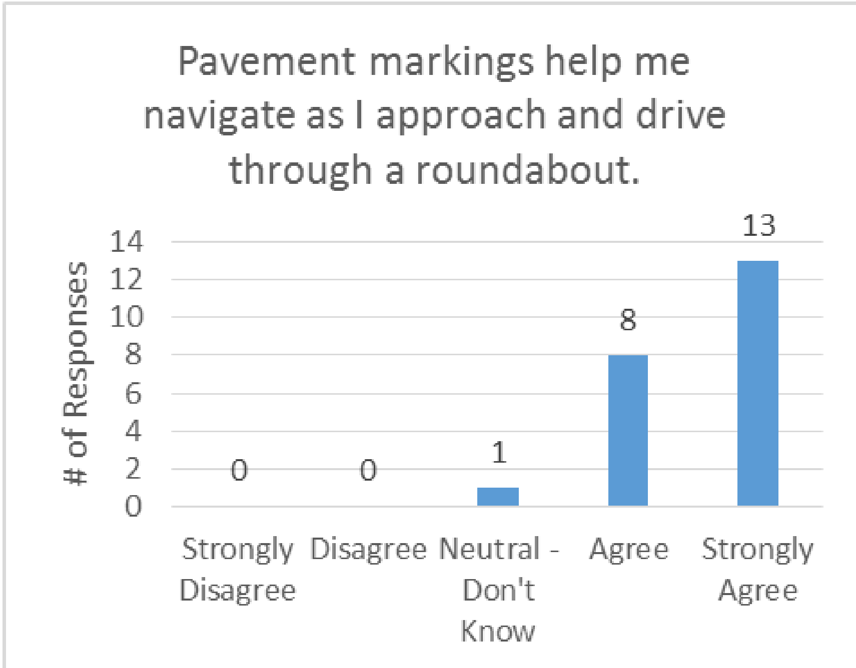

Figure 52. Chart. Questionnaire results for "Pavement markings help me navigate as I approach and drive through a roundabout."

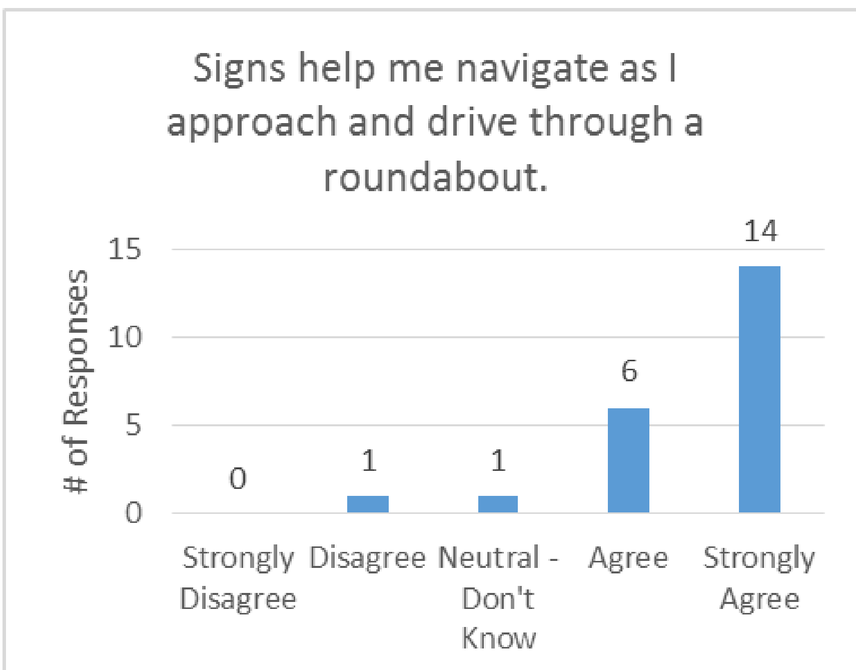

Figure 53. Chart. Questionnaire results for "Signs help me as I approach and drive through a roundabout."

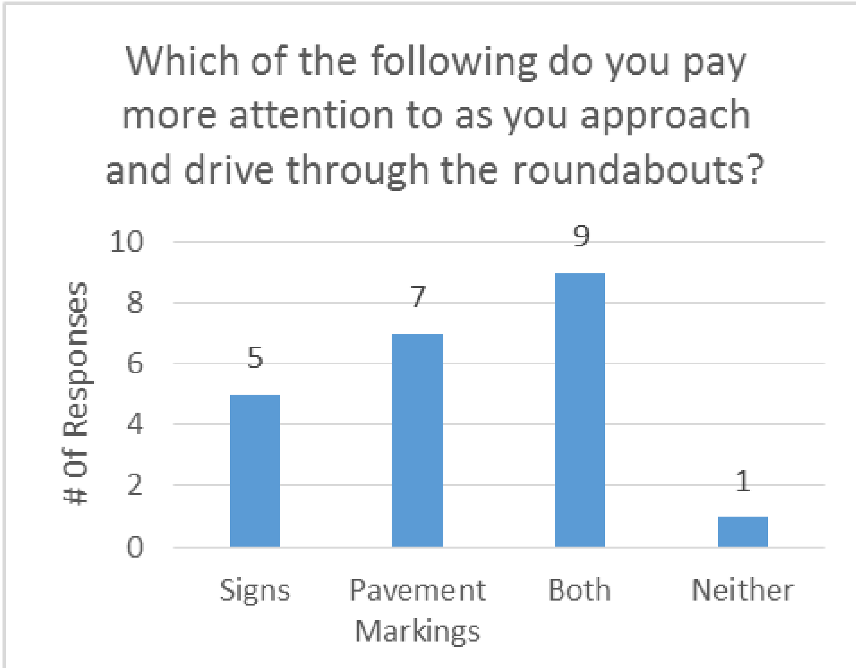

Figure 54. Chart. Questionnaire results for "Which of the following do you pay more attention to as you approach and drive through the roundabouts?"

APPENDIX D. EYE-TRACKER STUDY MANEUVERS (HILLIARD, OH)

The maneuvers performed by the participant drivers at each of the roundabouts in Hilliard, OH, are shown in figure 51, figure 52, figure 53, figure 54, figure 55, and figure 56.

Figure 55. Diagrams. Hilliard OH roundabout - Main St. and Scioto Darby St.

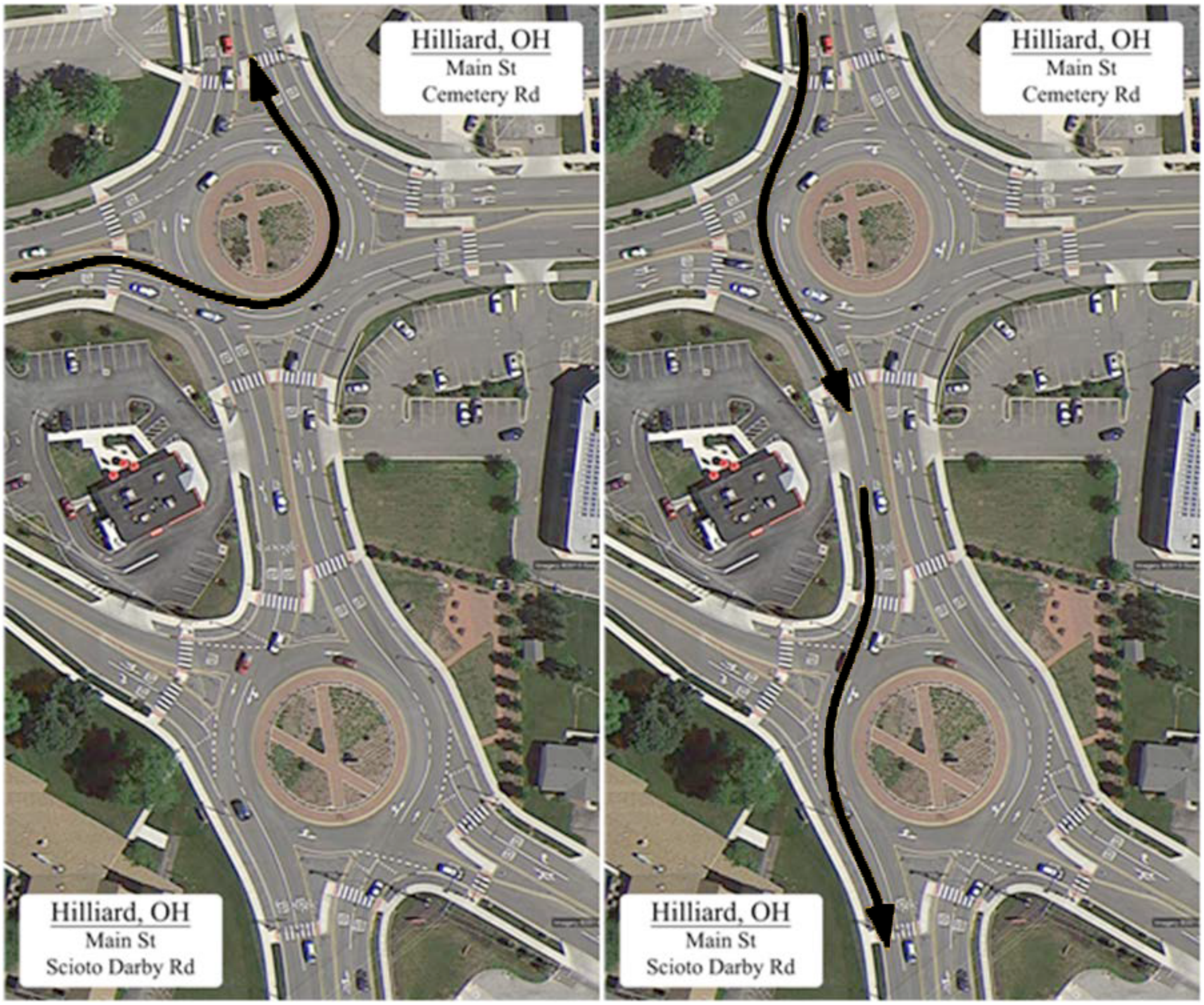

Figure 56. Diagrams. Hilliard OH roundabout - Main St. and Cemetery Rd.

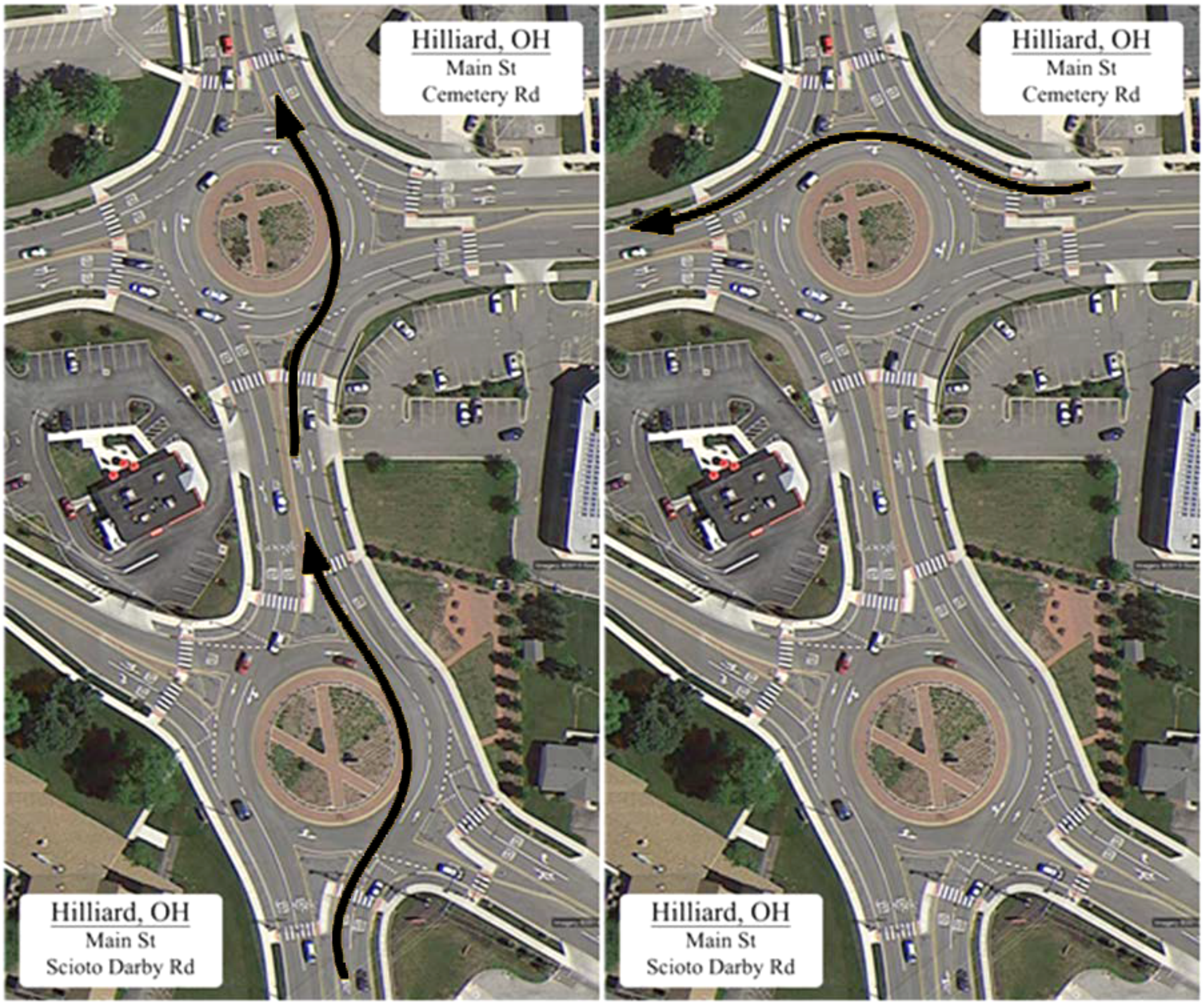

Figure 57. Diagrams. Hilliard OH roundabout - Main St., Cemetery Rd., and Scioto Darby Rd.

Figure 58. Diagrams. Hilliard, OH roundabout - Leap Rd. and Anson Dr.

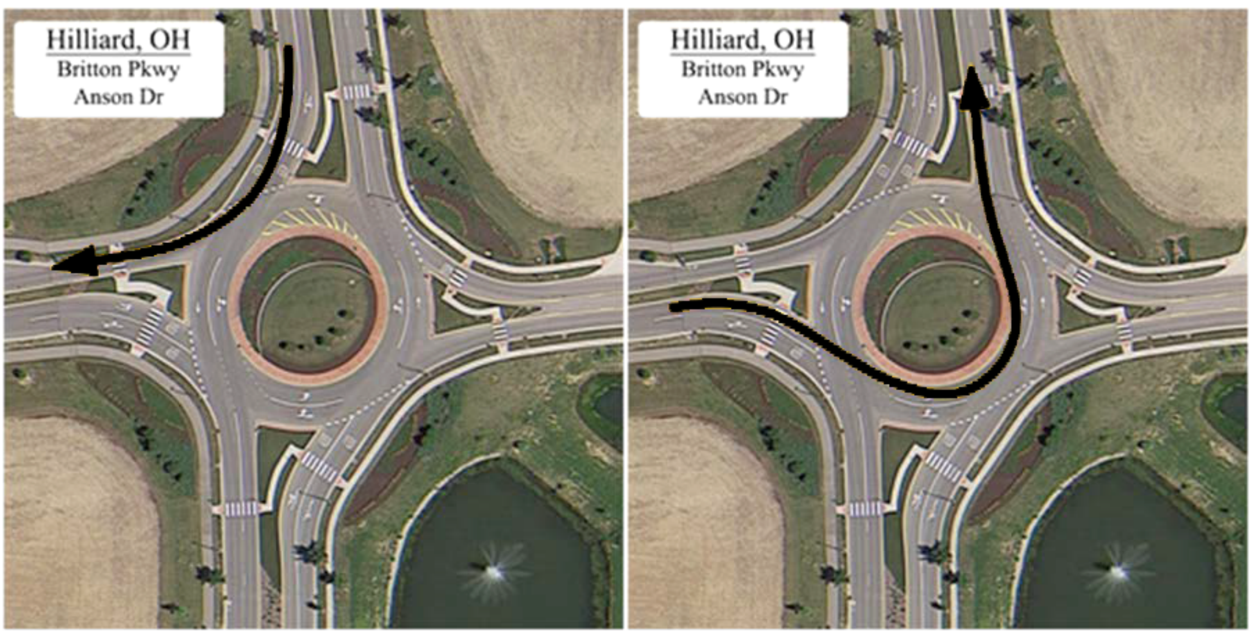

Figure 59. Diagrams. Hilliard, OH roundabout – Britton Pkwy and Anson Dr.

Figure 60. Diagram. Hilliard, OH roundabout – Britton Pkwy and Davidson Rd.

APPENDIX E. EYE-TRACKER STUDY MANEUVERS (CARMEL, IN)

The maneuvers performed by the participant drivers at each of the roundabouts in Carmel, IN are shown in figure 57, figure 58, figure 59, and figure 60.

Figure 61. Diagrams. Carmel, IN roundabout – Old Meridian St. and Grand Blvd.

Figure 62. Diagrams. Carmel, IN roundabout – Old Meridian St. and N. Pennsylvania St.

Figure 63. Carmel, IN roundabout – Clay Terrace Blvd, North Roundabout.

Figure 64. Carmel, IN roundabout – Clay Terrace Blvd, South Roundabout.

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