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National Surface Transportation Safety Center for Excellence

Pedestrian Visibility in Roundabouts:

Naturalistic Study of Driver Eye-Glance Behavior

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ABSTRACT

Roundabouts increase safety, but their safety effects on vulnerable road users are not as great as the safety effects for motor-vehicle drivers. Additionally, many motorists fail to yield to pedestrians at intersections and roundabouts, possibly because drivers do not see the pedestrians, crosswalk signage, and/or pavement markings. Eye-tracking technology has been used to quantify driver eye-glance behavior in a variety of driving contexts, but has yet to be applied to drivers in roundabouts with pedestrians. The exploratory research performed for this project attempted to shed light on driver visual behavior at roundabouts, and to examine the extent that drivers looked at pedestrians, with the ultimate goal of increasing pedestrian safety at roundabouts. A quasi-naturalistic experimental study was conducted and drivers' mean fixation durations toward pedestrians located at crosswalks were measured at two different roundabouts while making three kinds of turn maneuvers (straight through, left turn, and right turn) under day and nighttime conditions. Three important findings were evident. First, the results show that the position of the vehicle within the roundabout (*approach*, *entry,* and *exit*) had a significant impact on drivers' visual behavior toward pedestrians. Drivers looked at pedestrians longer when they (drivers) were at the *approach* portion of the roundabout and less at the *entry* and *exit* portions of the roundabout. Second, the number of lanes at the roundabout did not significantly affect the drivers' fixation durations toward the pedestrians. Finally, the age of the drivers and time of day did not significantly influence fixation durations toward the pedestrians at the roundabouts.

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CHAPTER 1. INTRODUCTION

More roundabouts are being installed in the U.S. (Rodegertds et al., 2007) and decades of research have documented their positive effects on traffic safety (Daniels, Brijs, Nuyts, & Wets, 2010a, 2010b; Gross, Lyon, Persaud, & Srinivasan, 2013; Hyden & Varhelyi, 2000). Researchers do not agree on the safety effects of roundabouts on all road users, especially vulnerable road users, such as pedestrians, cyclists, and motorcycle riders (Daniels et al., 2010a, 2010b; Daniels, Nuyts, & Wets, 2008). Motorist yield rates are low, and Departments of Transportation and other stakeholders struggle to raise these rates (Huang, Zegeer, & Nassi, 2000; Inman, Davis, & Sauerburger, 2006). This study aims to shed light on driver behavior in roundabouts with respect to pedestrians by measuring drivers' eye-glance behavior. Although a number of studies have examined driver eye-glance behavior (Birrell & Fowkes, 2014; Konstantopoulos, Chapman, & Crundall, 2010; Martens & Fox, 2007; Schnell & Zwahlen, 2007; Zwahlen, Russ, & Schnell, 2002), none have measured driver eye-glance behavior with respect to pedestrian visibility on a roundabout. The exploratory research performed here addresses this gap, with the ultimate goal of improving pedestrian safety.

BACKGROUND

A great deal of research has been performed on the effect of roundabouts on traffic safety, including research on crash rates, roundabout geometry and crashes, and driver response to roundabout markings and signage. Below we summarize some of this research.

Roundabouts and Crash Rates

When roundabouts are installed, crash rates go down, and traffic flow, in general, improves (Montella, 2011). Roundabouts slow traffic because they force drivers to steer laterally around the central island. Slowing traffic reduces crash risk and improves pedestrian safety (Pasanen & Salmivaara, 1993; Retting, Ferguson, & McCartt, 2003). Roundabouts also eliminate the need for a left-hand turn, and keep all traffic flowing in the same direction (Hyden & Varhelyi, 2000). Reducing the number of directions in which traffic can travel in turn reduces the number of vehicle conflict points—points where drivers' intentions might conflict, possibly causing a crash. Typical four-way signalized intersections have 32 potential vehicle-vehicle conflict points, whereas roundabouts have only eight (Gross et al., 2013).

One method to quantify the safety effects of roundabouts is to examine crash rates before and after installation (Gross et al., 2013; Hyden & Varhelyi, 2000). A study of 21 junctions in a small Swedish city that were temporarily replaced with roundabouts led to no generalized safety conclusions because of the nature of the study (lower speeds and traffic volumes), but speeds were lowered, and conflicts changed from more-dangerous front-front conflicts to less-dangerous side-side conflicts (Hyden & Varhelyi, 2000). Rodegertds et al. (2007) found that roundabouts in the U.S. improve crash rates, especially injury-causing crash rates, but also suggested that roundabouts should be better designed to reduce pedestrian and cyclist crashes.

Regional differences have been observed in driver behavior at roundabouts. For example, California drivers' critical headways (the minimum time interval in a roundabout's circulating flow during which a vehicle can safely enter) were within those defined by Rodegertds et al.

(2007), but the follow-up headways (the distance between two entering vehicles) in California were shorter (Xu & Tian, 2008) than those in the rest of the country as specified by (Rodegertds et al., 2007).

Many studies have focused on roundabouts replacing non-signalized intersections, but Gross et al. (2013) studied the effects of changing signalized intersections to roundabouts. They found that conversions to roundabouts resulted in fewer crashes and far fewer injury crashes. The effects were greater for suburban areas than urban areas, and greater for four-way than for three-way intersections (Gross et al., 2013).

Driver Behavior at Roundabouts

The above studies examined aggregate driver behavior through roundabouts. Roundabouts have been successfully used as speed calming measures; a study conducted by Silva, Santos, Vasconcelos, Seco, and Silva (2014) reported that speed reductions in the range of 26% to 37% were observed. Other research has focused on behavior at the driver level and the factors influencing driver behaviors. Drivers use top-down processing to achieve their goals, but also use bottom-up processing to react to salient features on the roadway (Summala & Rasanen, 2000). Because drivers search for signs and traffic in expected locations, for example looking left to check oncoming traffic when approaching a roundabout, they might overlook cyclists on the right, especially if the cyclists are not conspicuous and do not capture bottom-up attention (Summala & Rasanen, 2000). In a similar manner, using habitual search patterns might interfere with pedestrian detection at roundabouts, especially if pedestrians and pedestrian crossings are not visually salient. Just as drivers are more likely to make errors at intersections, especially when they can make a right turn at a red light and fail to see a pedestrian (Young, Salmon, & Lenne, 2013), when entering a roundabout they may look for oncoming traffic to the left, but neglect to check the right for cyclists and pedestrians before proceeding.

Roundabout Design and Driver Responses

A number of factors in roadway and signage design affect crash risk at roundabouts. In an Italian study on 15 roundabouts with different geometries, problems in geometry were associated with 60% of crashes (Montella, 2011). Most crashes (54%) were at the entry (head-on and rear-end were the most common in that category), followed by crashes at the exit (20%, rear-end also common) and in the circulating roadway (19%; Montella, 2011). The main risk factors were drivers failing to yield, too large of a central island, and poor signage. Although Montella (2011) found an effect of geometry on crash rates, Rodegertds et al. (2007) found the effect of geometry to be less important than the effects of variations in driver behavior. Daniels et al. (2010a) found that inscribed circle diameter, island diameter, road width, and number of lanes did not affect crash severity in roundabouts. More research is needed on roundabout geometry and traffic safety, especially with respect to vehicle-pedestrian conflicts.

Signage also affects driver behavior. Poor signage (missing, poorly located, and faded signs) contributed to over half of crashes where pedestrians were struck at roundabout exits (Montella, 2011). In the U.S., different sign designs were examined to see which design resulted in motorists choosing the correct entry lane in a multilane roundabout. The results showed that drivers only selected the correct lane at a rate slightly better than chance, but that diagrammatic signs showing an icon of the roundabout performed better than other sign types (Katz, Hanscom, & Inman, 2005). Signage and road markings influence motorist behavior, but also need to be further researched and optimized.

Roundabouts and Pedestrian Safety

Pedestrians, along with cyclists and motorcycle riders, are particularly vulnerable at roundabouts. Roadway and crosswalk design and signing influence pedestrian and motor-vehicle driver behavior, and various studies have attempted to quantify the effect with the goal of increasing pedestrian safety. The first group of studies focused on pedestrian and motorist behavior at intersections and sections of straight roadway. Van Houten and Malenfant (1999) found that advanced stop lines and a sign with roving eyes increased pedestrians' likelihood to search for motor vehicles, but a countdown timer and conspicuous crosswalk markings did not. At four-way intersections, raised crosswalks and a larger refuge island increased pedestrians' use of crosswalks, while bulb-outs resulted in fewer pedestrians using crosswalks (Huang & Cynecki, 2000). Refuge islands caused more pedestrians to cross in the pedestrian-crossing area without reducing pedestrian vigilance, and marked crosswalks increase driver yielding behavior (Nee & Hallenbeck, 2003). Additionally, cones with a sign saying, "State law – yield to pedestrians in crosswalk in your half of the road" resulted in 81.2% of drivers stopping for pedestrians, compared to 69.8% stopping when no cones were present (Huang et al., 2000). An overhead crosswalk sign caused yield rates to increase from 45.5% to 52.1%, but a pedestrian-activated sign saying "stop for pedestrians in crosswalk" reduced yield rates from 62.9% to 51.7% (Huang et al., 2000).

Roundabout-specific studies include Weber (2012), who compared various crosswalk designs at roundabouts. He attempted to maximize pedestrian visibility to drivers and pedestrian-refuge width (width or island between lanes), and to minimize the impact of vehicles waiting for pedestrians on traffic flow, pedestrian walking distance and exposure in the crosswalk, and vehicle speed in the crosswalk. The resulting recommendation was to locate crosswalks one car length from the roundabout's exit side (Weber, 2012). A separate study found that when a legally blind pedestrian stood at a roundabout crosswalk, drivers yielded 16.7% of the time when the roundabout had signs and rumble strips, compared to 11.5% before the signs and rumble strips were installed (Inman et al., 2006). The studies performed on pedestrian and driver behavior show that driver yielding rates are highly varied, and that signage and road treatments have a mixed effect on yield rates. More research is needed to determine how to best warn drivers that pedestrians are present and encourage them to yield.

DRIVER EYE-GLANCE BEHAVIOR

The effect of roadway markings and signage on driver visual behavior at roundabouts is not fully understood. One way to examine where drivers look is to record their eye-glance behavior. Eye-glance behavior has been used to help quantify driver vigilance by monitoring the percentage of eye closure (PERCLOS) to indicate drowsiness (Bergasa, Nuevo, Sotelo, Barea, & Lopez, 2006; Rau, 2005), and using glance direction to measure driver distraction (Birrell & Fowkes, 2014; Olson, Hanowski, Hickman, & Bocanegra, 2009; Sodhi, Reimer, & Llamazares, 2002). Different device types can measure driver eye-glance behavior. A common one—and the one used in this research—has two cameras. One infrared camera is aimed at the driver's eye and tracks pupil position. Another video camera captures an image of what the driver sees. After the system is calibrated, the images from the two cameras can be overlaid and used to determine what the driver is looking at, irrespective of head position (Arrington Research, 2013).

Fixation Duration

A great deal is known about driver eye-glance behavior on typical roadways. Drivers usually scan no more than 15° to the left and right while driving (Green, 2007), and the highest percentage of fixations (13.5%) are 0.5° to the right and 0.5° below the horizon (Zwahlen, 1989). The distribution of glances is close to logarithmic; there are few very short glances, many short glances, and some very long glances, so mean glance duration, effective in describing variables with a normal distribution, should not necessarily be the sole measure quantifying eye-glance behavior (Green, 2007). Men have glance durations 11% longer than those of women, older people have glance durations 5% longer than those of young people, and glance durations are longer at night than during the day (Green, 2007; Konstantopoulos et al., 2010). Novice drivers tend to fixate 10 to 20 meters closer than experienced drivers (Green, 2007) and have a narrower angle of search (6.2°) than experienced drivers 10.6° (Konstantopoulos et al., 2010). Drivers have fewer and longer glances at night and in the rain, and that effect occurs with both novice and experienced drivers (Konstantopoulos et al., 2010).

Fixation Location

Drivers tend to fixate on the vehicle in front of them, and they look to the horizon and to the right for signs (Green, 2007). On curves, drivers tend to look at the edge lines more than directly in front of them, and they look toward the inside of the curve (Green, 2007). About one-fifth of fixations are outside the visual area that would promote safe driving (Green, 2007). New drivers read more signs than those familiar with the road (Green, 2007; Martens & Fox, 2007). Drivers tend to look at signs of different types the same number of times, except for stop signs and stop-ahead signs, which receive six times as many looks as other sign types at night and 3.8 times as many looks as other sign types during the day (Zwahlen et al., 2002). Diagrammatic signs, which are useful in promoting correct lane choice to those entering roundabouts (Katz et al., 2005), do not appear to distract drivers by receiving too many looks (Zwahlen et al., 2002). Although much is known about driver eye-glance behavior, no studies found have examined driver eye-glance behavior at roundabouts, focusing on fixations on pedestrians. The research presented in this report explores that gap in knowledge.

SUMMARY

Roundabouts increase safety, but their safety effects on vulnerable road users are not as great as the safety effects for motor-vehicle drivers. Additionally, many motorists fail to yield to pedestrians at intersections and roundabouts, possibly because drivers do not see the pedestrians, crosswalk signage, and/or pavement markings. Eye-tracking technology has been used to quantify driver eye-glance behavior in a variety of driving contexts, but has yet to be applied to drivers in roundabouts with pedestrians. The exploratory research performed for this project attempted to shed light on driver visual behavior at roundabouts, and to examine the extent that drivers looked at pedestrians, with the ultimate goal of increasing pedestrian safety at roundabouts.

CHAPTER 2. METHOD

PARTICIPANTS

Twenty-four participants from Virginia Tech Transportation Institute's (VTTI) participant database were recruited to take part in the study. Participants had a valid U.S. drivers' license and were administered a visual acuity test prior to participation. Participants were allowed to wear corrective lenses for the driving session if they indicated they used them while driving. A minimum visual acuity of 20/40 (6/12) for both eyes was required to participate in the study.

EXPERIMENTAL DESIGN

This quasi-naturalistic study took place in downtown Blacksburg, Virginia, and on the Virginia Tech campus. Participants drove through two roundabouts where confederate pedestrians were positioned, and the participants' eye-glance behavior was recorded. Other factors, like traffic and non-confederate pedestrians, were not controlled because this study was performed on public roads. However, the data collection took place at similar times of the day so that the traffic patterns were similar across participants. This study utilized a mixed-factorial design. The variables are listed in Table 1.

Table 1. Independent variables used in the experiment.

Variable	Levels
Roundabout Location	Campus (Single-Lane), Town (Two-Lane)
Vehicle Location	Approach, Entry, Exit
Time of Day	Day, Night
Age	Young, Old

INDEPENDENT VARIABLES

Time of day and age were between-subjects variables. Roundabout location and vehicle location were within-subjects variables.

Time of Day

Twelve participants drove during the day, and another 12 participants drove during the night. Night runs were conducted after civil twilight.

Age

The participant sample was age and gender balanced. Participants were divided into two age groups: younger (18–35 years) and older (over 65 years). These two age groups captured not only a wide range of driving experiences but also a broad range of visual capabilities.

Roundabout Locations

Two three-way roundabouts were chosen for this study. One was a single-lane roundabout on the Virginia Tech campus with higher pedestrian traffic. The other was a two-lane roundabout in the town of Blacksburg with higher vehicular traffic. Sidewalks at both roundabout locations were lighted. Both are shown in Figure 1.

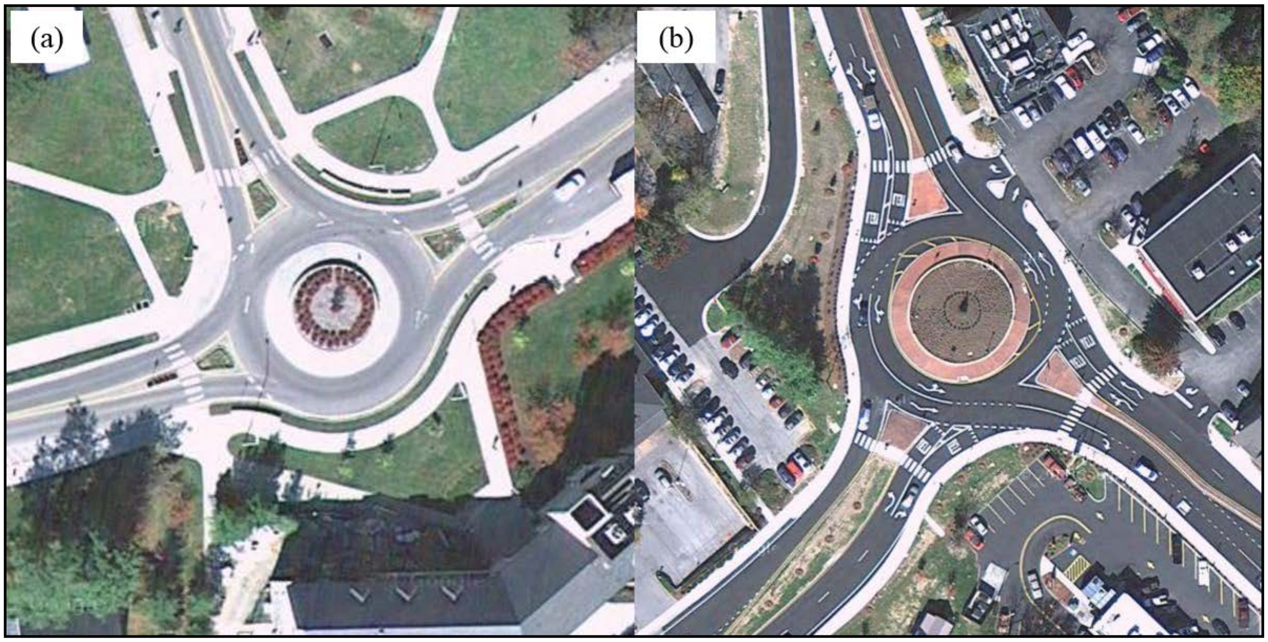

Figure 1. Photo. (a) Single-lane roundabout and (b) two-lane roundabout used in study (Google Maps, 2016).

Vehicle Location

Since a vehicle's location in the roundabout affects driver eye-glance behavior, its position was analyzed with respect to the dependent variables. Vehicle location was divided into three regions: (1) *approach*; (2) *entry*; and (3) *exit*. *Approach* was where the vehicle first passed the divider to the island. *Entry* was from the entry crosswalk to where the driver started looking toward the roundabout's exit (by observing several drivers' eye glances), and was predetermined for every turn maneuver at each roundabout. *Exit* was from the end of the entry to approximately 10 feet after the exit crosswalk. The three vehicle locations are shown for two turns in Figure 2.

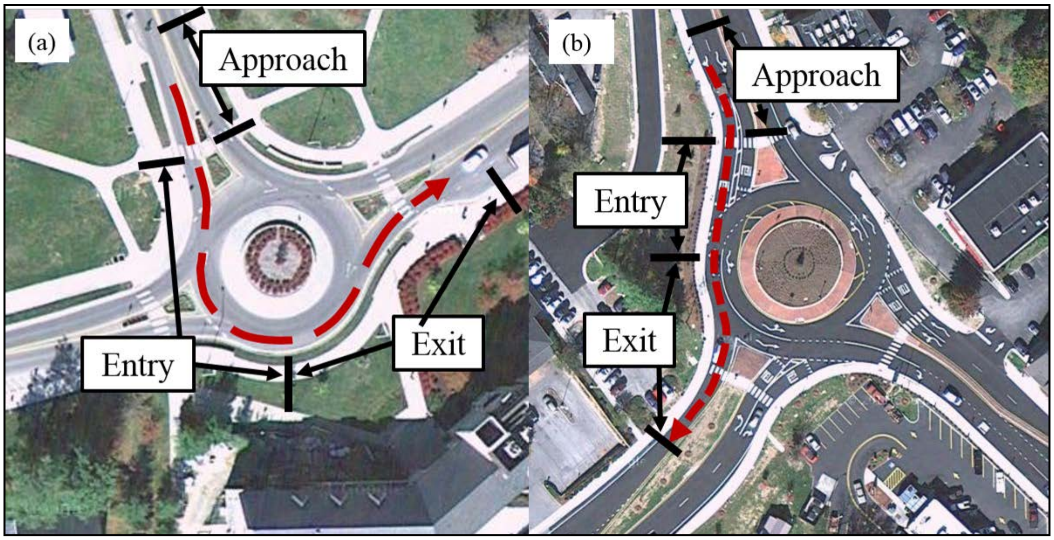

Figure 2. Photo. Vehicle location for both roundabouts: (a) left turn; (b) right turn (Google Maps, 2016).

DEPENDENT VARIABLES

Fixation Duration

The main dependent variable in this study was mean fixation duration toward a pedestrian while driving through roundabouts. It was calculated as the mean duration of each of the participant's fixations on the pedestrian, measured in milliseconds.

EQUIPMENT

Test Vehicle

One sport-utility vehicle was used in the study: a 1999 Ford Explorer. The vehicle was instrumented with a data acquisition system (DAS), which included digital audio and video recorders, and Global Positioning System (GPS) receivers. The data collected included driving distance, vehicle speed, and GPS location.

Eye Tracker

To measure eye-glance behavior, an eye tracker and its accompanying software were used (ViewPoint EyeTracker®, Arrington Research, Phoenix, AZ). The eye tracker was mounted on a pair of clear goggles and had two cameras—one under each eye—to measure where the pupil was aimed. The eye tracker had a third camera mounted on the goggles over the bridge of the nose, aiming forward, to take video of the scene the user was facing. After calibration, the software overlaid a dot corresponding to gaze direction, determined by where the pupil was aimed, onto the video images taken with the forward-facing camera. The goggles did not restrict head movement and allowed participants to view any part of the scene. All of the cameras were connected to a personal computer (PC) through a video frame grabber card.

The eye cameras used an infrared illumination to locate the pupil in the image of the eye. When the eye cameras located the pupil, the system was then calibrated to overlay the pupil's position on the correct point relative to the pixels in the forward camera's field of view. The calibration procedure took approximately 15 minutes per participant.

The system could calculate eye movement to an accuracy of between 0.25° and 1° of visual arc, and the spatial resolution of the system was approximately 0.15° of visual arc. The data collection rate used for this study was 60 Hz. The eye data included X and Y gaze position, pupil height and width, ocular torsion, delta time, total time, and fixation durations.

PROCEDURE

In this study, a group of on-road experimenters acted as pedestrians. An in-vehicle experimenter rode in the vehicle with the participant, guiding the participant through the procedure, coordinating the position of the on-road experimenters acting as pedestrians, and ensuring that the eye-tracking hardware and software were functioning.

Recruitment was performed via the VTTI participant database. First, a general description of the study was provided to participants so they could decide if they were willing to participate. If they were interested, participants completed questionnaires to determine their eligibility based on driver license status and health. Eligible participants were scheduled to come in for a driving session.

When participants arrived at VTTI, they read and signed an informed consent form. The in-vehicle researcher escorted the participant to the test vehicle and the participant was familiarized with its operation. Participants did not know that pedestrians were being placed at the roundabouts; they were informed that their visual behavior while driving through different kinds of roadways was being studied. A researcher also fit the participant with the eye-tracker system and calibrated it. The participant was directed to drive through the selected route, which included both roundabouts. The eye-tracking system was set to record. Participants made all possible turn maneuvers in both roundabouts. Maneuvers included right turn, left turn, and going straight through the roundabout. During the experiment, all three maneuvers were executed for each approach at both roundabouts. Confederate researchers played the role of pedestrians. They stood at three locations with respect to the vehicle's path through the roundabout: (1) the crosswalk where the vehicle entered; (2) the crosswalk where the vehicle exited; or (3) hidden out of sight. The approximate pedestrian positions are shown in Figure 3, and were dependent on the vehicle's maneuver through the roundabout for a particular run. The in-vehicle researcher notified the on-road researcher acting as a pedestrian when the vehicle was approaching. Pedestrian presentation was randomized with blanks (no pedestrian presentations). When the experiment was complete, the in-vehicle researcher directed the participant to return to VTTI. Participants were compensated $30 per hour for their time.

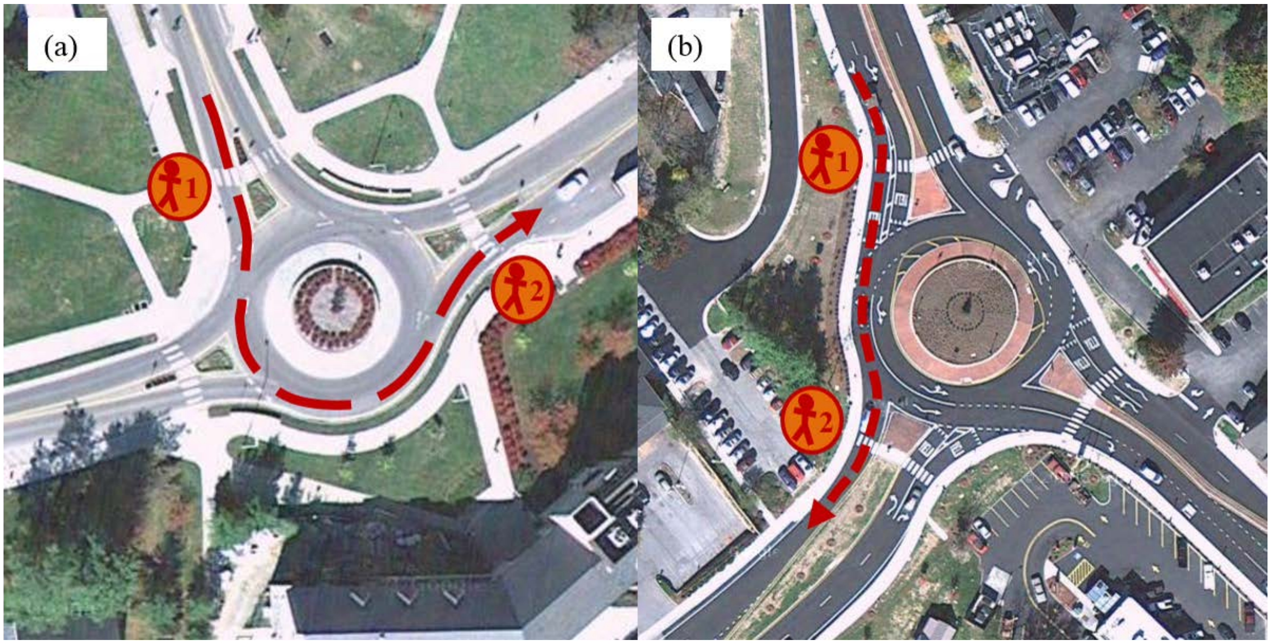

Figure 3. Photo. Pedestrian positions for both roundabouts for (a) left turn and (b) right turn: (1) entry crosswalk; (2) exit crosswalk (Google Maps, 2016).

POST PROCESSING

Before analyzing fixation duration with respect to the independent variables, the data were divided by vehicle location (*approach*, *entry*, and *exit*). Researchers watched the eye-glance video and identified when the vehicle reached each location. Specifically, the beginning of *the approach* vehicle location was marked as the point when the vehicle first reached the divider island. The end of the *approach* vehicle location and the beginning of the *entry* vehicle location was marked as the point when the vehicle reached the entry crosswalk. The end of the *entry* vehicle location and the beginning of the *exit* vehicle location was marked as the point when the driver first looked to the exit. Finally, the end of the *exit* vehicle location was marked as the point when the vehicle was approximately 10 feet past the exit crosswalk.

Once the beginning and ending frame numbers for each vehicle location were identified, a custom MatLab® program extracted eye glances toward pedestrians for those periods. The eye-tracker software reported fixation duration, number of fixations, and X-Y position with respect to the forward-facing camera for each frame. In the eye-tracker videos, a green dot representing the driver's gaze direction was overlaid on video of the driver's view taken with the forward-facing camera. Researchers identified the frames where the green dot, or driver fixation, overlaid the pedestrian and recorded the frame numbers at the beginning and end of each fixation. From this, the mean fixation duration toward the pedestrian was calculated.

STATISTICAL ANALYSIS

A linear mixed model (LMM) analysis was run on mean fixation duration with age, vehicle location, roundabout location, and time of day as fixed effects. Participant identification number nested within age by time of day was used as a random effect. The alpha level was established at

0.05. For significant effects, post hoc analyses (pairwise comparisons) were performed using least square means with Tukey's honest significant difference (HSD) to control for family-wise error rate. Three models were run, one for each type of turn maneuver executed at the roundabout: straight through, left turn, and right turn.

CHAPTER 3. RESULTS

STRAIGHT-THROUGH MANEUVER

Table 2. LMM results of straight-through maneuvers. Significant effects are shown in bold.

Effect	Num DF	Den DF	F Value	P Value
Age	1	16.8	2.6	0.1257
Vehicle Location	**2**	**53.5**	**12.32**	**<.0001**
Age × Vehicle Location	2	53.5	0.17	0.8427
Location	1	29.5	1.64	0.2104
Age × Location	1	29.5	0.65	0.4258
Vehicle Location × Location	2	44.5	0.42	0.6578
Age × Vehicle Location × Location	2	44.5	0.1	0.9072
Time of Day	1	16.8	0.22	0.6445
Age × Time of Day	1	16.8	0.08	0.7825
Vehicle Location × Time of Day	2	53.5	0.66	0.5228
Age × Vehicle Location × Time of Day	2	53.5	1.82	0.1717
Location × Time of Day	1	29.5	2.98	0.0948
Age × Location × Time of Day	1	29.5	0.44	0.5113
Vehicle Location × Location × Time of Day	2	44.5	0.24	0.7862
Age × Vehicle Location × Location × Time Of Day	2	44.5	0.37	0.696

The results of the LMM for straight-through maneuvers are in shown in Table 2. For vehicles going straight through the roundabouts, fixation duration was significantly different across the three vehicle locations: $F(2, 53.5) = 12.32$, $p < 0.0001$. Pairwise comparisons revealed that mean fixation durations between *approach* and *entry*, $t(51.3) = 4.54$, $p < 0.0001$, and *approach* and *exit*, $t(58.3) = 4.01$, $p = 0.0002$, were significantly different. Mean fixation durations at approach, entry, and exit for straight-through maneuvers are shown in Figure 4. Mean fixation duration toward pedestrians at the *approach* ($M = 34.44$ ms) was significantly longer than at *entry* ($M = 4.67$ ms) and *exit* ($M = 6.32$ ms).

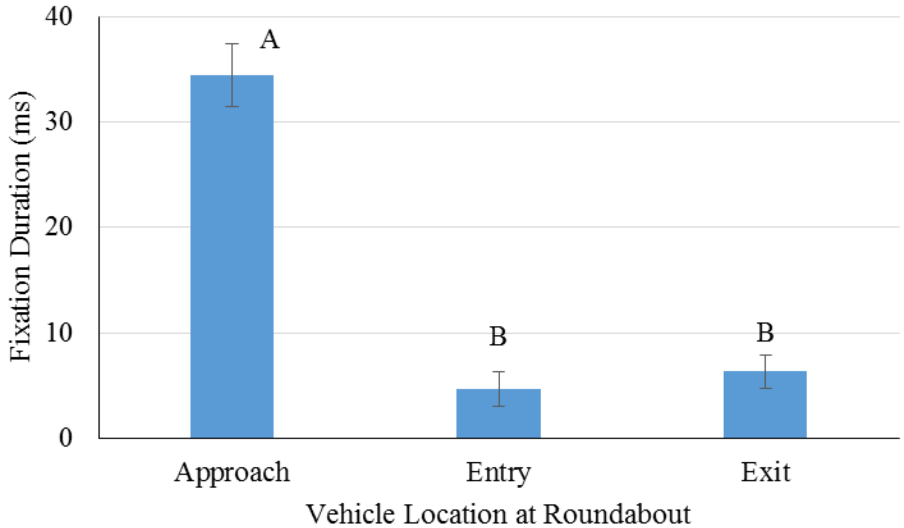

Figure 4. Chart. Mean fixation duration toward pedestrians at approach, entry, and exit for straight-through maneuvers. Error bars reflect standard errors. Uppercase letters indicate significant post hoc pairwise comparisons ($p < 0.05$).

LEFT TURNS

Table 3. LMM results for left turns. Significant effects are shown in bold.

Effect	Num DF	Den DF	F Value	P Value
Age	1	32.3	0	0.992
Vehicle Location	**2**	**64.6**	**9.97**	**0.0002**
Age × Vehicle Location	2	64.6	0.19	0.8238
Location	1	47.1	3.43	0.0703
Age × Location	1	47.1	0.06	0.8061
Vehicle Location × Location	**2**	**60.8**	**4.14**	**0.0206**
Age × Vehicle Location × Location	2	60.8	0.04	0.9603
Time of Day	1	32.3	0	0.9757
Age × Time of Day	1	32.3	0.4	0.5307
Vehicle Location × Time of Day	2	64.6	0.41	0.6644
Age × Vehicle Location × Time of Day	2	64.6	0.25	0.7827
Location × Time of Day	1	47.1	1.48	0.2304
Age × Location × Time of Day	1	47.1	0.11	0.745
Vehicle Location × Location × Time of Day	2	60.8	1.35	0.268
Age × Vehicle Location × Location × Time Of Day	2	60.8	0.02	0.9809

The results of the LMM for left turns are in shown in Table 3. For vehicles turning left, fixation durations were significantly different across vehicle locations: $F(2, 64.6) = 9.97$, $p = 0.0002$. Post hoc pairwise comparisons indicated the mean fixation durations between *approach* and *entry*, and *approach* and *exit*, were significantly different. The interaction between vehicle location and roundabout location was also significant: $F(2, 60.58) = 4.14$, $p = 0.0206$. Upon further analysis, it was revealed that fixation duration was significant only across the three vehicle locations at the campus (single-lane) roundabout: $F(2, 64.9) = 13.58$, $p < 0.0001$. At this roundabout, mean fixation duration toward the pedestrian was significantly longer at *approach* (M = 46.03 ms) than at *entry* (M = 2.15 ms) and *exit* (M = 1.19 ms). This interaction also enabled comparisons of mean fixation durations in vehicle locations across the two different roundabouts. Mean fixation durations across the town (M = 12.56 ms) and campus (M = 46.03 ms) roundabouts significantly differed only at the *approach* vehicle location, $t(79.5) = 3.52$, $p = 0.0007$. Mean fixation durations for each roundabout at every vehicle location are illustrated in Figure 5.

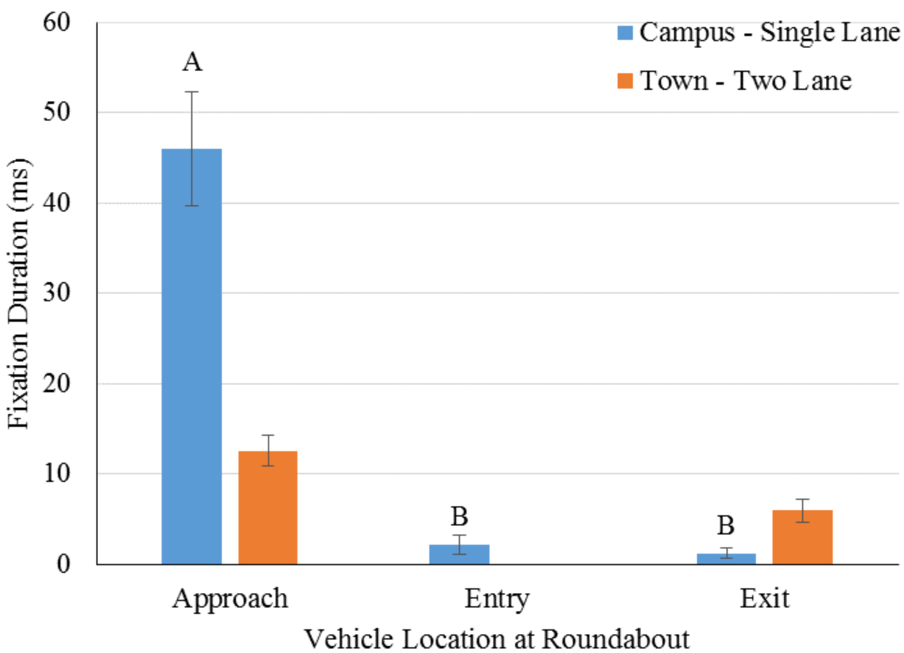

Figure 5. Chart. Two-way interaction between vehicle location and roundabout location. Error bars reflect standard errors. There were no glances towards pedestrians at the entry in town. Uppercase letters indicate significant post hoc pairwise comparisons (p < 0.05) within each location.

RIGHT TURNS

Table 4. LMM results of right turns. Significant effects are shown bold.

Effect	Num DF	Den DF	F Value	P Value
Age	1	12	1.34	0.269
Vehicle Location	**2**	**50**	**18.13**	**< .0001**
Age × Vehicle Location	2	50	0.05	0.9472
Location	1	12	1.32	0.2725
Age × Location	1	12	0	0.99
Vehicle Location × Location	2	50	1.33	0.2742
Age × Vehicle Location × Location	2	50	0.1	0.9016
Time of Day	1	12	1.38	0.2626
Age × Time of Day	1	12	1.55	0.2363
Vehicle Location × Time of Day	2	50	0.23	0.7973
Age × Vehicle Location × Time of Day	2	50	0.23	0.7966
Location × Time of Day	1	12	0.37	0.5569
Age × Location × Time of Day	1	12	0	0.9466
Vehicle Location × Location × Time of Day	2	50	0.5	0.6075
Age × Vehicle Location × Location × Time Of Day	2	50	0.22	0.8025

The results of the LMM for right turns are in shown in Table 4. For vehicles turning right, fixation duration significantly differed across vehicle location (*approach*, *entry*, and *exit*): $F(2, 50) = 18.13$, $p < 0.0001$. Pairwise comparisons indicated that the mean fixation durations between the *approach* and *entry*, $t(62.5) = 5.18$, $p < 0.0001$, and between the *approach* and *exit*, $t(80.3) = 4.88$, $p < 0.0001$, were significantly different. Mean fixation durations of pedestrians at the three vehicle locations are illustrated in Figure 6. Once again, mean fixation duration toward the pedestrian at the *approach* ($M = 33.11$ ms) was significantly longer than at *entry* ($M = 2.11$ ms) and *exit* ($M = 4.93$ ms).

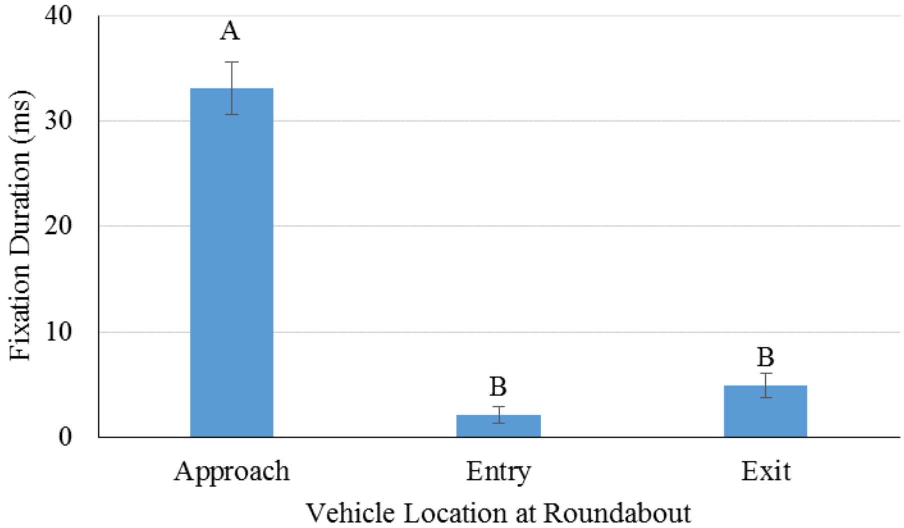

Figure 6. Chart. Mean fixation duration toward pedestrians at approach, entry, and exit for right turns. Error bars reflect standard errors. Uppercase letters indicate significant post hoc pairwise comparisons ($p < 0.05$).

CHAPTER 4. DISCUSSION

The goal of this project was to understand if a vehicle's location within a roundabout had a significant effect on drivers' eye glance behavior, and more specifically, their fixation duration toward pedestrians located at the entry and exit of crosswalks. To this end, a quasi-naturalistic experimental study was conducted and drivers' mean fixation durations toward pedestrians located at crosswalks were measured at two different roundabouts while making three kinds of turn maneuvers (straight through, left turn, and right turn) under day and nighttime conditions.

Three important findings were evident. First, there were significant differences in the drivers' fixation durations toward the pedestrians, and these fixation durations were dependent on the drivers' location within the roundabout. Second, the number of lanes at the roundabout did not significantly affect the drivers' fixation durations toward the pedestrians. Finally, the age of the drivers and time of day did not significantly influence fixation durations toward the pedestrians at the roundabouts.

The results clearly show that the position of the vehicle within the roundabout (*approach, entry,* and *exit*) had a significant impact on drivers' visual behavior toward pedestrians. Drivers looked at pedestrians longer when they (drivers) were at the *approach* portion of the roundabout and less at the *entry* and *exit* portions of the roundabout. For the straight-through maneuver, mean fixation durations toward the pedestrians at *entry* and *exit* were lower by about 86% and 82%, respectively. At the left turns, they were lower by about 97% and 87%, respectively. At the right turns, they were lower by about 94% and 85%, respectively, compared to mean fixation duration at the *approach* vehicle position. These differences in drivers' visual behavior toward pedestrians could be because drivers look left for a gap in traffic when *entering* a roundabout but do not do so when *approaching* one. Such scanning-for-a-gap behavior interferes with a pedestrian search, which would occur to the right. At the *entry,* as defined for this project, the vehicle had passed the entry crosswalk and was ready to enter the roundabout, making it less likely for a pedestrian to cause a conflict than another vehicle, thus influencing driver scanning. Furthermore, the sight distance of the pedestrian located at the exit crosswalk is lower than that of the pedestrian at the entry crosswalk, which could also contribute to the pedestrian at *approach* to the roundabout receiving a longer mean fixation duration.

Accounting for the shorter fixation times toward the pedestrian at the roundabout exit is one of the biggest challenges in designing crosswalks at intersections. While approaching the roundabout, drivers have sufficiently longer fixations toward pedestrians, but while exiting the roundabout they might not have enough time to scan for pedestrians. Moreover, a driver who is already in the roundabout and looking to exit it might think that they have the right-of-way. Pedestrians at the exit might also think that they have the right-of-way because of the crosswalk. This leads to a dangerous situation at the exit of the roundabout, where the vehicle and the pedestrian both think that they have right-of-way, which could lead to pedestrian crashes. This problem becomes even more severe for pedestrians who are visually impaired. When a crosswalk is placed close to the roundabout, drivers who are exiting the roundabout are more likely to have a right-of-way conflict with pedestrians at the exit. This driver dilemma at a critical location within a roundabout has the potential to not only cause pedestrian–vehicle crashes at the exit but also to cause rear-end crashes within the roundabout if vehicles brake late after seeing a pedestrian. Moving the pedestrian crosswalks further away from roundabouts could alleviate this issue; however, more research is required to evaluate this assumption.

Interestingly, roundabout location (or number of lanes) did not significantly influence the mean fixation durations toward the pedestrian for straight-through and right-turn maneuvers. For left turns at the town roundabout (two-lane), there was no difference in the mean fixation durations toward pedestrians between the vehicle locations, and there were no glances toward pedestrians while in the *entry* to the roundabout. Furthermore, for the left-turn maneuvers, the mean fixation durations at the town roundabout were significantly longer than those at the campus roundabout (by approximately 73%) only at the *approach* vehicle location. These longer fixation durations during left turns could be attributed to the higher vehicular traffic at the location and the number of lanes at the town roundabout. Drivers might have paid more attention to vehicles present in the roundabout and in the other lanes at the busier roundabout. Consequently, their fixation durations toward pedestrians were shorter than those at the campus roundabout.

Neither age (driving experience) of the participants nor the time of the day significantly affected mean fixation durations toward pedestrians. This was not expected, as it was assumed that driving experience and ambient lighting levels might influence eye-glance behavior (Green, 2007; Konstantopoulos et al., 2010). However differences in the results of the current study could be due to different methodologies and objectives of research. In the study mentioned by Green (2007), drivers' fixation times were studied in open-road situations (not specifically at roundabouts like the current study), and the research by Konstantopoulos et al. (2010) was conducted in a driving simulator. Thus, further research is required to understand the effect of age and time of day on driver eye-glance behavior at roundabouts.

There were some limitations in the study. It is extremely hard to predict crash risk to a pedestrian based on the fixations toward them as crashes are extreme events and the fixations of drivers prior to a crash are almost impossible to capture. Further, it is also very difficult to know if a driver safely detected the pedestrian at the roundabout by looking at the fixation durations because a gaze point is not necessarily the point of visual attention. However, existing research in eye movements shows that when there are differences in the locations of gaze and visual attention, the succeeding gazes are always toward the location of visual attention (Rayner, 1978). Therefore, it could be argued that pedestrian locations at roundabouts that had lower fixation durations did not significantly capture drivers' visual attention. The lower visual attention could affect crash risk as it has been shown to be a predictor for crash risk, especially for older drivers (Ball, Owsley, Sloane, Bruni, & Roenker, 1993).

CHAPTER 5. CONCLUSION

At a time when roundabouts are gaining popularity in the U.S. because they reduce crash frequency and severity, the results of this study have important implications for pedestrian safety. The results of the study indicate that vehicle location within a roundabout (*approach*, *entry*, and *exit*) plays an important role in eye-glance behavior toward pedestrians. Pedestrians located at the exit crosswalk of the roundabout receive significantly shorter fixation durations than those at the approach crosswalk. This shorter fixation duration could lead to potential crash scenarios between vehicles and pedestrians at the exits. The results of this study increase our understanding of driver eye-glance behavior at roundabouts. These results also indicate that eye-tracking technologies can be an effective tool for assessing pedestrian safety at roundabouts.

REFERENCES

Arrington Research. (2013). *Viewpoint eye tracker: Products and accessories 2013*.

Ball, K., Owsley, C., Sloane, M., Bruni, J., & Roenker, D. (1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Invest Ophthalmol Vis Sci, 34*, 3110-3123.

Bergasa, L. M., Nuevo, J., Sotelo, M. A., Barea, R., & Lopez, M. E. (2006). Real-time system for monitoring driver vigilance. *IEEE Transactions on Intelligent Transportation Systems, 7*(1), 63-77. doi:10.1109/Tits.2006.869598

Birrell, S. A., & Fowkes, M. (2014). Glance behaviours when using an in-vehicle smart driving aid: A real-world, on-road driving study. *Transportation Research Part F-Traffic Psychology and Behaviour, 22*, 113-125. doi:10.1016/j.trf.2013.11.003

Daniels, S., Brijs, T., Nuyts, E., & Wets, G. (2010a). Explaining variation in safety performance of roundabouts. *Accident Analysis and Prevention, 42*(2), 393-402. doi:10.1016/j.aap.2009.08.019

Daniels, S., Brijs, T., Nuyts, E., & Wets, G. (2010b). Externality of risk and crash severity at roundabouts. *Accident Analysis and Prevention, 42*(6), 1966-1973. doi:10.1016/j.aap.2010.06.001

Daniels, S., Nuyts, E., & Wets, G. (2008). The effects of roundabouts on traffic safety for bicyclists: An observational study. *Accident Analysis and Prevention, 40*(2), 518-526. doi:10.1016/j.aap.2007.07.016

Green, P. (2007). Where do drivers look while driving (and for how long?). In R. E. Dewar & P. L. Olson (Eds.), *Human Factors in Traffic Safety* (2nd ed., pp. xvi, 533 p.). Tucson, AZ: Lawyers & Judges Pub. Co.

Gross, F., Lyon, C., Persaud, B., & Srinivasan, R. (2013). Safety effectiveness of converting signalized intersections to roundabouts. *Accident Analysis and Prevention, 50*, 234-241. doi:10.1016/j.aap.2012.04.012

Huang, H., & Cynecki, M. J. (2000). Effects of traffic calming measures on pedestrian and motorist behavior. *Transportation Research Record, 1705*(1), 26-31.

Huang, H., Zegeer, C., & Nassi, R. (2000). Effects of innovative pedestrian signs at unsignalized locations - Three treatments. *Transportation Research Record, 1705*(1), 43-52.

Hyden, C., & Varhelyi, A. (2000). The effects on safety, time consumption and environment of large scale use of roundabouts in an urban area: A case study. *Accident Analysis and Prevention, 32*(1), 11-23. doi:10.1016/S0001-4575(99)00044-5

Inman, V. W., Davis, G. W., & Sauerburger, D. (2006). *Pedestrian access to roundabouts: Assessment of motorists' yielding to visually impaired pedestrians and potential treatments to improve access* (FHWA-HRT-05-080). Springfield, VA: National Technical Information Service.

Katz, B. J., Hanscom, F. R., & Inman, V. W. (2005). *Navigation Signing for Roundabouts*. Retrieved from https://www.atssa.com/...file/Navigation_Signing_for_Roundabouts.pdf

Konstantopoulos, P., Chapman, P., & Crundall, D. (2010). Driver's visual attention as a function of driving experience and visibility. Using a driving simulator to explore drivers' eye movements in day, night and rain driving. *Accident Analysis and Prevention, 42*(3), 827-834. doi:10.1016/j.aap.2009.09.022

Martens, M. H., & Fox, M. (2007). Does road familiarity change eye fixations? A comparison between watching a video and real driving. *Transportation Research Part F-Traffic Psychology and Behaviour, 10*(1), 33-47. doi:10.1016/j.trf.2006.03.002

Montella, A. (2011). Identifying crash contributory factors at urban roundabouts and using association rules to explore their relationships to different crash types. *Accident Analysis and Prevention, 43*(4), 1451-1463. doi:10.1016/j.aap.2011.02.023

Nee, J., & Hallenbeck, M. E. (2003). *A motorist and pedestrian behavioral analysis relating to pedestrian safety improvements* (WA-RD 560.1). Olympia, WA: Washington State Department of Transportation.

Olson, R. L., Hanowski, R. J., Hickman, J. S., & Bocanegra, J. (2009). *Driver distraction in commercial vehicle operations* (FMCSA-RRR-09-042). Washington, DC: United States Department of Transportation.

Pasanen, E., & Salmivaara, H. (1993). Driving speeds and pedestrian safety in the City of Helsinki. *Traffic engineering and control, 34*(6), 308-310.

Rau, P. S. (2005). *Drowsy driver detection and warning system for commercial vehicle drivers: Field operational test design, data analyses, and progress* (Paper #05-0192). 19th International Conference on Enhanced Safety of Vehicles.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85*(3), 618-660. doi:10.1037/0033-2909.85.3.618

Retting, R. A., Ferguson, S. A., & McCartt, A. T. (2003). A review of evidence-based traffic engineering measures designed to reduce pedestrian-motor vehicle crashes. *American Journal of Public Health, 93*(9), 1456-1463.

Rodegertds, L., Blogg, M., Wemple, E., Myers, E., Kyte, M., Dixon, M., . . . Carter, D. (2007). *NCHRP Report 572: Roundabouts in the United States*. Washington, DC: Transportation Research Board.

Schnell, T., & Zwahlen, H. T. (2007). Driver preview distances at night based on driver eye scanning recordings as a function of pavement marking retroreflectivities. *Transportation Research Record: Journal of the Transportation Research Board, 1692*, 129-141.

Silva, A. B., Santos, S., Vasconcelos, L., Seco, Á., & Silva, J. P. (2014). Driver behavior characterization in roundabout crossings. *Transportation Research Procedia, 3*, 80-89. doi:https://doi.org/10.1016/j.trpro.2014.10.093

Sodhi, M., Reimer, B., & Llamazares, I. (2002). Glance analysis of driver eye movements to evaluate distraction. *Behavior Research Methods Instruments & Computers*, *34*(4), 529-538. doi:10.3758/Bf03195482

Summala, H., & Rasanen, M. (2000). Top-down and bottom-up processes in driver behavior at roundabouts and crossroads. *Transportation Human Factors, 2*(1), 29-37.

Van Houten, R., & Malenfant, J. E. L. (1999). *Canadian research on pedestrian safety* (FHWA-RD-99-090). Washington, DC: Federal Highway Administration.

Google Maps. (2016). [Blacksburg, Virginia]. Retrieved from https://www.google.com/maps/@37.228333,-80.4208503,1868m/data=!3m1!1e3

Weber, P. (2012). *An examination of pedestrian crosswalk design at roundabouts*. Paper presented at the 2012 Annual Conference of the Transportation Association of Canada, Fredericton, New Brunswick.

Xu, F., & Tian, Z. Z. (2008). Driver behavior and gap-acceptance characteristics at roundabouts in California. *Transportation Research Record*(2071), 117-124. doi:10.3141/2071-14

Young, K. L., Salmon, P. M., & Lenne, M. G. (2013). At the cross-roads: An on-road examination of driving errors at intersections. *Accident Analysis and Prevention*, *58*, 226-234. doi:10.1016/j.aap.2012.09.014

Zwahlen, H. T. (1989). Conspicuity of suprathreshold reflective targets in a driver's peripheral visual field at night. *Transportation Research Record: Journal of the Transportation Research Board, 1213*, 35-46.

Zwahlen, H. T., Russ, A., & Schnell, T. (2002). *Driver eye scanning behavior while viewing ground-mounted diagrammatic guide signs before entrance ramps at night*. Paper presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, DC.