

Simulator Study of Driver Responses to Pedestrian Treatments at Multilane Roundabouts

Katayoun Salamati, Bastian Schroeder, Nagui M. Roupail, Christopher Cunningham, Yu Zhang, and David Kaber

Previous studies have shown that roundabouts, especially multilane roundabouts, pose accessibility challenges to pedestrians with vision impairments, in part because of a lack of yielding by drivers, especially on multilane roundabout exit legs. In this study, a driving simulator was used to assess three different treatments in regard to their propensity for increasing the driver yielding rate. These treatments were the relocation of the stop bar and crosswalk away from the beginning of the exit leg and two types of beacons, namely a pedestrian hybrid beacon (PHB) and a rectangular rapid flashing beacon (RRFB). The study showed that the installation of any kind of beacon (PHB or RRFB), with or without crosswalk relocation, increased driver yielding rates significantly. Relocating the crosswalk did not provide a significant increase in the driver yielding rate for the base case, but appeared to enhance further the effectiveness of the PHB and RRFB treatments. The results of using an eye tracker on drivers to track their gaze pattern while exiting the roundabout showed that having a beacon installed with crosswalk relocation increased drivers' attention on the beacon and on the pedestrian along the road. However, some of the participants failed to see and react to the pedestrian treatments and thus caused concern about the visibility of these treatments at the roundabout exit leg.

Several studies have shown that roundabouts pose accessibility challenges for pedestrians who are blind or otherwise visually impaired (1–4). Although geometric elements of a roundabout are designed to promote speed reduction within the circle (5), drivers' speeds are higher when they are exiting the roundabouts, compared with when entering (4, 6). As a consequence, studies have shown that driver yielding rates to pedestrians standing at the exit leg of roundabouts are lower compared with at the entry (7). The purpose of this work is to test the effect of different treatments aimed at increasing driver yielding rates to pedestrians at the exit leg of roundabouts. The focus on the exit leg of a two-lane roundabout is justified in an effort to focus study resources on the crosswalk location that is documented to pose the greatest accessibility challenges (4, 6).

K. Salamati, B. Schroeder, N. M. Roupail, and C. Cunningham, Institute for Transportation Research and Education, North Carolina State University, NCSU Campus Box 8601, Raleigh, NC 27695-8601. Y. Zhang and D. Kaber, Edward P. Fitts Department of Industrial and Systems Engineering, North Carolina State University, 448 Daniels Hall, Raleigh, NC 27695-7906. Corresponding author: K. Salamati, Katy_Salamati@ncsu.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2312, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 67–75.
DOI: 10.3141/2312-07

The background and literature on pedestrian accessibility to modern roundabouts, the findings on drivers' yielding process to pedestrians, and the effects of potential treatments on increasing the driver yielding rate are presented next. The following section presents the objective of the research. The methodology section describes the process for designing the driver simulation experiment as well as sample size calculations, subject population attributes, and challenges. Next, the findings and results of the driving simulator and eye tracker data are discussed. Finally, conclusions and recommendations for future work are provided.

BACKGROUND AND LITERATURE REVIEW

Title II of the Americans with Disabilities Act requires that “new and altered facilities constructed by, on behalf of, or for the use of state and local government entities be designed to be readily accessible to and usable by people with disabilities (28 CFR 35.151)” (1). Various studies have shown that roundabouts (multilane) are not readily accessible to visually impaired and blind pedestrians (2, 3). Although design speeds vary according to the geometric design, roundabouts are intended to promote speed reduction in the circulating lanes. However, when exiting a roundabout, drivers are accelerating, thus reducing their propensity to yield at the exit legs relative to entry (8). Geruschat and Hassan, among others, found that drivers are more likely to yield to pedestrians at the entry than at the exit (6). Results from NCHRP Report 674 also indicate the probability of a pedestrian encountering a yield is higher on the entry lane than on the exit lane; for one roundabout the yielding rates for entry versus exit are 90% and 58%, respectively (4).

Although roundabouts are proved to be operationally safe and efficient for motorists when the roundabouts are operating below capacity, they do impose accessibility challenges for pedestrians with visual impairments (8). The TRB Roundabout Informational Guide suggests that roundabout signalization may be beneficial under three conditions: high vehicular volume, high pedestrian volume, and accessibility at more complex crossing situations (8). This FHWA recommendation is related to a recently released Notice of Proposed Rule-Making by the U.S. Access Board that calls for the use of accessible pedestrian signals at newly constructed roundabouts with multilane approaches (9). To avoid the cost and uncertain effectiveness of full signalization schemes, nonsignalization treatments have been put forward to improve accessibility at complex roundabouts (4).

The *Manual on Uniform Traffic Control Devices* (MUTCD) has authorized the use of a new pedestrian crossing treatment, the

pedestrian hybrid beacon (PHB), also known as a HAWK, as a device intended to “warn and control traffic at signalized locations” and help pedestrians cross the street by having a red signal indication (10). Fitzpatrick et al. conducted research on the safety effects of PHB signals installed at uncontrolled pedestrian crossings and showed an 86% decrease in pedestrian crashes (11, 12). A separate study of PHBs indicated that the number of pedestrian crashes had decreased compared with reference sites with no PHB (13). The study also reported high rates of driver compliance with PHBs, which resulted in a higher driver yielding rate to pedestrians at the crossing location. NCHRP 674 tested a system of PHBs at a two-lane roundabout in Golden, Colorado, to increase accessibility for blind and visually impaired pedestrians (4). The report concluded that the average (blind) pedestrian’s delay while trying to cross the street dropped from 16.0 s to 5.9 s, and more important, the occurrence of potential vehicle–pedestrian collisions fell from 2.8% to 0.0%. As with other previous studies, NCHRP 674 indicated that the driver compliance rate was not 100% with the installation of a PHB at a two-lane roundabout and reported a 12.6% red light running rate (4). Regardless of the findings on PHBs, they are supported as an alternative to signalization by the U.S. Access Board (9).

Another type of beacon sanctioned in the MUTCD is the rectangular rapid flashing beacon (RRFB). Shurbutt and colleagues studied the effect of the RRFB on the yielding rate and found that installation of side-mounted RRFBs at multilane uncontrolled crosswalk locations increased the driver yielding rate, on average from 18.2% to 87.8% (14, 15). Hunter et al. evaluated the effect of an RRFB at a trail crossing in Florida and reported that instances of drivers’ yielding to cyclists and pedestrians increased significantly compared with the no-beacon condition. However, the report mentions that “. . . the device is not fail safe, and communities employing the device, especially at trail crossings, should take note of this . . .” and suggests that there be additional effort to educate drivers and residents about the RRFB device (13). The RRFB system is being considered as a potential treatment for improving accessibility in upcoming research by FHWA, but at the present time the RRFB system is not mentioned explicitly as an alternative to pedestrian signals by the U.S. Access Board (9).

OBJECTIVE

This research aimed to explore driver yielding behavior to pedestrians at the exit leg of roundabouts. Three different treatments were assessed in regard to their propensity for increasing the driver yielding rate at the exit leg of roundabouts. The treatments were stop bar and crosswalk relocation away from the roundabout and two types of beacons, a PHB and an RRFB. In particular, the research addressed the following questions:

- Does the presence of either beacon improve driver yielding rates over a regular crosswalk base scenario?
 - Which type of beacon produces a higher driver yielding rate?
 - Does the location of the crosswalk relative to the circulating lane affect the driver yielding rate?
 - Is yielding behavior (or lack thereof) related to drivers consciously ignoring the pedestrian at the crosswalk or to a lack of awareness?

The last question aimed to distinguish between drivers who saw the pedestrian or the treatment or both, but decided (consciously) not to

yield, and those who did not notice the pedestrian or the treatment or both. Relocating the crosswalk further away from the roundabout had some disadvantages, including adding to walking distance for the pedestrians and the potential for higher speeds for the vehicles when exiting.

METHODOLOGY

The research team used a driving simulator equipped with an eye tracker device for this study. Using a driving simulator was cost-effective compared with field studies. Using the simulator also allowed the research team to conduct a controlled experiment with respect to the location of the crosswalk, pedestrians, traffic volume, and type of treatment. The driving simulator software also simplified the data collection process for the experiment in the sense that all participants were exposed to exactly the same stimulus conditions (although in a randomized order). The simulator also enabled the team to collect different types of data related to driver behavior and driver attentiveness through the use of an eye tracker system. The eye tracker provided valuable information about drivers’ eye movements and gaze patterns in the process of yielding (or not yielding) to the pedestrian while exiting the roundabout. The following sections discuss the equipment used to conduct the study, the experimental design, and the measures used to test the effectiveness of the simulated treatments.

Driving Simulator

An STISIM Drive M400 driving simulator (System Technology, Inc.) located in the Ergonomics Lab of the Industrial Engineering Department at North Carolina State University was used for the study. The driving simulator was interactive and had a modular steering unit with full-sized steering wheel, semiadjustable car seat, turn indicator, speedometer, modular accelerator and brake pedal unit, adjustable speed-sensitive steering force-feel system, horn, and audio system. Three 37-in. HDTV monitors provided a 135-degree field of view for the driving environment. STISIM Drive software allowed the logging of various types of data for each trial such as speed of the drivers at any time and point, acceleration, deceleration, and lane changing (16).

Eye Tracker

Eye trackers were mounted on participants’ heads to track their pupil movements on the screen (17). An H6 head-mounted optics eye-tracking system can accurately track the pupil diameter and eye position relative to the person’s head. The eye trackers provided valuable information about the drivers’ gaze patterns during driving as they entered and exited the roundabouts. Figure 1 shows a screenshot of the driving simulator as well as the eye tracker device while the PHB is being approached.

Experimental Design

The research team designed an experiment with the driving simulator to test a side-mounted RRFB and overhead-mounted PHB compared with a standard crosswalk base scenario at the exit legs of multilane roundabouts. In addition, the team tested two offset distances from the circulating lane to the crosswalk, measured



FIGURE 1 Roundabout simulation: (a) driving simulator screenshot and (b) eye tracker used in the study. (Source for 1b: Ergolab at North Carolina State University.)

at 20 and 60 ft (6.1 and 18.3 m) from the beginning of the exit leg. The pedestrian crosswalk and beacons were installed with reference to the location of the stop bar according to MUTCD guidelines (10).

The simulator experiment was designed as a full factorial experiment with two factors, the stop bar distance measured upstream of the exit leg and the type of beacon. The type of beacon factor had three levels, PHB, RRFB, and control (no-beacon) condition (CTRL). The full factorial combination generated six unique scenarios (CTRL20, PHB20, RRFB20, CTRL60, PHB60, and RRFB60). Each scenario simulated an urban corridor of eight roundabouts located at a constant spacing of 2,000 ft (610 m). Four of the roundabouts had one pedestrian standing at the crosswalk with one foot on the crosswalk. This design thus allowed for subject replication. The location of the roundabouts with a pedestrian was randomized across each of the scenarios. The use of buildings, trees, pedestrians walking along the sidewalk, and traffic helped create a realistic urban environment. The roundabouts were modeled with an hourly flow rate of approximately 200 vehicles for the subject approach, to ensure operations well below capacity. The modeling of a congested roundabout and the associated gap acceptance

rules for simulated vehicles (other than the subject driver) was not possible with the available simulator technology. The roundabouts had two entering and exiting lanes in each approach, each 12 ft (3.66 m) wide, and two circulating lanes in the circle. The center islands had a diameter of 150 ft (45.75 m) and the speed limit was 35 mph (56 km/h).

Each participant was asked to drive all six scenarios. The team decided not to advise the participants about the true purpose of the study so as not to bias their yielding behavior in the experiment. Instead, drivers were told that the experiment was geared at studying roundabout corridors and to drive the scenarios as they would naturally drive while observing the traffic rules and regulations to the best of their knowledge. A Latin square design for 6 × 6 experiments was used to randomize the order of scenarios for each subject (18). To eliminate any learning effects, each driver was asked to drive one additional scenario at the end of the experiment, which was a repetition of the first scenario. That process should have allowed the team to account for any learning effects during the experiment. Table 1 shows the six different patterns for the order of scenarios. For the purpose of this paper, only the results of Orders 2 through 7 are presented, after treating the first scenario as a pilot run.

TABLE 1 Latin Square Design for Randomizing the Order of Trials

Pattern	Randomized Order of Scenarios						
	1st	2nd	3rd	4th	5th	6th	7th
1	CTRL20	CTRL60	RRFB20	PHB60	PHB20	RRFB60	CTRL20
2	PHB20	CTRL20	PHB60	RRFB20	RRFB60	CTRL60	PHB20
3	RRFB20	PHB60	CTRL60	RRFB60	CTRL20	PHB20	RRFB20
4	CTRL60	RRFB20	RRFB60	PHB20	PHB60	CTRL20	CTRL60
5	RRFB60	PHB20	CTRL20	CTRL60	RRFB20	PHB60	RRFB60
6	PHB60	RRFB60	PHB20	CTRL20	CTRL60	RRFB20	PHB60

Each participant was randomly assigned one of the six patterns, while ensuring that overall an equal number of scenarios were achieved across all subjects. For example, a participant assigned to Pattern 2 would start with the PHB20 case (treated as a practice run), followed by CTRL20, PHB60, RRFB20, RRFB60, CTRL60, and PHB20. The randomization of scenarios was intended to account for any learning effects or changes in driver behavior over time. With four pedestrians present in each scenario, a total of 24 usable data points for each participant was generated, with four within-subject replications of each of the six scenarios.

Sample Size Calculation

Because the goal was to report whether drivers yielded to a pedestrian at the crosswalk exit leg, the experiments resulted in a success or failure. Therefore the binomial distribution was used to calculate the required sample size. There are no published results on the prevailing yielding rates at roundabout exits for the RRFB. However, NCHRP 674 reports a 22% yielding rate to pedestrians at a channelized turn lane with a flashing beacon installed (4). The same source also cited an approximately 87.4% yielding rate in both lanes of a two-lane roundabout, entry and exit, with a PHB installed (4). NCHRP 572 reported an average yielding rate of 29% for roundabouts across the United States (19). These values were chosen to calculate the sample size for the base scenario and each beacon scenario. The significance value (alpha) was chosen to be 0.05, and the power at 0.8. With a two-sided test and with the approximate success rates discussed above, the resulting sample size was estimated at 70 (20). The data were collected from 45 subjects, with four pedestrian crossings in each scenario; the sample size added up to 180, which allowed for multiple replications. The equation below was used for sample size calculations (20).

$$n = \frac{\left(z_{\alpha} \sqrt{(2PQ)} + z_{\beta} \sqrt{P_1Q_1 + P_2Q_2}\right)^2}{\sigma^2} \quad (1)$$

where

z_{α} = upper 100(1 - α) percentile of standard normal distribution,

z_{β} = upper 100(1 - β) percentile of standard normal distribution,

$$\sigma = P_2 - P_1; P_2 > P_1$$

= sample size standard deviation,

$$P = \frac{1}{2}(P_2 + P_1)$$

= success rate, and

$$Q = \frac{1}{2}(Q_1 + Q_2), Q = 1 - P$$

= failure rate.

Driver Population

The participant population was limited to drivers with 20/20 vision without wearing eyeglasses or contact lenses. The study was performed in Raleigh, North Carolina, on the campus of North Carolina State University, and subjects were recruited by using fliers distributed on campus and to businesses around the campus and by sending e-mails to people on a few e-mail lists, such as previous participants in a driver simulator project.

Of the 45 subjects, 60% were male and 40% female, and the age distribution ranged from 19 to 60 years. A set of debriefing questions was developed to ascertain the subjects' driving experience and for gauging their understanding of the elements of the study, including driving simulators, different beacons, stop bar distance, and how they felt about yielding to pedestrians when exiting the roundabouts. Table 2 depicts the results from the first portion of the questionnaire, which gives information about the sample driver population and driving habits. The debriefing questionnaire was given to participants after all scenarios were completed so as not to bias their behavior.

Table 2 shows drivers' perception rate of their yielding to pedestrians at roundabouts. On average, participants reported that they yielded to pedestrians at the exit leg of roundabouts 70% of the time. This percentage was assumed to be for roundabouts without any special pedestrian treatment. The fraction yielding at other uncontrolled intersections with pedestrians was 80%.

Measures of Effectiveness

For the purposes of this study, the measure of effectiveness extracted from the driving simulator was the driver yield rate to pedestrians in each scenario. Later in the results section, the driver yielding rate was analyzed on the basis of different subject attributes, for example, driving experience and average weekly encounter with pedestrians.

The performance measures extracted from the eye tracker were the pupil fixation duration, the number of pupil fixations on each type of beacon and (or) pedestrians, as well as the percentage of fixations on different objects in the scene. Fixation was defined as "those eye movements that best indicate the locations of the viewer's (overt) visual attention" (21). Fixations were measured in milliseconds; thresholds are discussed later in the section on results.

Challenges

Because the driving simulator software was not designed to simulate roundabout and circular vehicular movements or, for that

TABLE 2 Participants' Driving Profile from Debriefing Questionnaire

Question Regarding Driving Profile	Average	SD	Min.	Max.
Duration of driving in United States with a driving license (years)	14.0	8.3	2.5	39.0
Average driving hours, per week (hours of typical weekday)	8.3	6.4	1.5	36.0
Average count of passing through roundabouts, per week	2.0	2.0	0	8.0
Average count of passing through intersections with pedestrian crossings, per week	6.2	5.2	0.3	24.0
Average reported yielding rate to pedestrians at uncontrolled intersections ^a (%)	80	22	20	100
Average reported yielding rate to pedestrians when exiting roundabouts ^a (%)	70	39	0	100

NOTE: SD = standard deviation; min. = minimum; max. = maximum.

^aDrivers were asked questions directly to gauge their perception of their yielding rate to pedestrians at intersections and roundabouts.

matter, different types of signals, the research team faced significant challenges in designing an acceptable roundabout environment. To overcome such challenges the roundabouts, including center islands, splitter islands, and pavement markings, were designed as 3-D objects and imported into the simulator. RRFBs and PHBs were also designed as 3-D objects and incorporated into the simulator software. The research team further simulated circular traffic movements in the roundabout. The team simulated the traffic by breaking down the vehicle movements into several straight and diagonal movements to create the appearance of circulating traffic, as well as right- and left-turning movements in the roundabout.

RESULTS

Yielding Rates

Each of the 45 subjects was exposed to four pedestrian crossings in each scenario; sample size was 180. Table 3 shows the yielding rate for each scenario. With the CTRL20 scenario as the base case, the table shows the increase in yielding percentage (% increase), the results of a z -test (z -score) to test the significance of each scenario with the base scenario, along with the associated p -value to determine whether results were significant at the 95% confidence level.

The results of the z -test show statistically significant differences between the base case (CTRL20) and scenarios with beacon installations ($\alpha = 0.05$, $\beta = 0.8$). Although not significant at the 95% confidence level, the CTRL60 scenario also showed positive signs of improvement over the base condition ($p = .054$), with an estimated 27.3% improvement. Although smaller than the beacon effects, this represents a potential low-cost modification to the roundabout that may help improve yielding propensity.

The pattern of improved yielding with relocating the crosswalk was also observed for the PHB60 and RRFB60, which resulted in the two highest overall yielding rates. In fact, relocating the PHB from 20 to 60 ft increased yielding from 68.3% to 85.6% (p -value = .00010), and relocating the RRFB from 20 to 60 ft resulted in an increase from 51.7% to 73.9% (p -value = .00001). The combined effect of higher yielding at an increased offset distance is an important finding, especially because higher offset distances have previously been linked by research to improved operational performance for vehicles, resulting in lower pedestrian-induced effects on vehicular delay over the standard crosswalk location (22).

In a comparison of the RRFB and PHB treatments, the PHB treatment generally resulted in somewhat higher yielding rates. At the 20-ft distance the PHB yielding rate of 68.3% exceeded the RRFB rate of 51.7% ($p = .00125$). Similarly, the PHB and RRFB yielding rates at 60 ft were 85.6% and 73.9%, respectively (p -value = .00591). Therefore, the PHB treatment generally resulted in improved yield-

ing behavior and the differences to the RRFB treatment were statistically significant at the 95% confidence level.

Further analysis was done to show the effect of different subject attributes on yielding rates. The team divided the subjects into two groups (i.e., less than or more than 10 years of driving experience) according to their duration of driving in the United States with a driver's license (experience), average hours of driving per week (driving), average count of passes through a roundabout per week (roundabout), and average count of passes through intersections with pedestrian crossings (pedestrians). The z -test was used to study whether there was a significant difference in yielding rates between the two groups for each of the above subject attributes. The results are summarized in Table 4 and discussed below. Effects with a p -value less than .05 are highlighted in bold.

Duration of Driving in the United States with Driver's License (Exposure)

The sample population was divided into two groups: drivers with less than and drivers with more than 10 years of driving experience in the United States. When a confidence level of 95% was used, the results of the z -test showed that there was no significant difference in yielding behavior between the two groups of drivers in the base scenario (CTRL20) and RRFB20. However, more driving experience resulted in significantly more yielding to pedestrians in the rest of the scenarios.

Average Hours of Driving per Week (Driving)

The yielding rate in each scenario appeared to be higher for subjects who, on average, drove more than 7 h per week. However, there was no significant difference between the yielding rate in each scenario, except for the PHB60 scenario. It appears that drivers with longer driving hours during the week are more responsive to the red indication of the PHB when the crosswalk and stop bar were relocated farther away from the roundabout ($p = .046$). The same behavior was observed for the RRFB with a confidence level of 90%.

Average Count of Passes Through a Roundabout per Week (Roundabout)

Table 4 shows results on the yielding behavior for drivers based on their weekly count of passing through roundabouts. Drivers who passed through roundabouts more than once a week had higher yielding rates than did drivers with fewer passes. However, the difference is significant only in the base scenario. These results suggest that drivers with more exposure in navigating roundabouts are more likely

TABLE 3 Yielding Rate Results for Each Scenario Compared with the Base (CTRL20) Scenario

Characteristic	Scenario					
	CTRL20	CTRL60	PHB20	PHB60	RRFB20	RRFB60
Yielding rate (%)	36.7	46.7	68.3	85.6	51.7	73.9
% increase	Base	27.3	86.4	133.3	40.9	101.5
z -score	Base	1.92	6.02	9.51	2.87	7.10
p -value	Base	.054	<.0001	<.0001	.0042	<.0001

TABLE 4 Subject Attribute's Effect on Driver's Yielding Behavior

Characteristic	Scenario					
	CTRL20	CTRL60	PHB20	PHB60	RRFB20	RRFB60
Experience ≤ 10 years (<i>n</i> = 68) (%)	30.9	30.9	52.9	73.5	45.6	63.2
Experience > 10 years (<i>n</i> = 112) (%)	40.2	56.3	77.7	92.9	55.4	80.4
<i>z</i> -score	1.25	3.31	3.46	3.58	1.27	2.54
<i>p</i> -value	.2095	.0009	.0005	.0003	.2035	.0112
Driving ≤ 7 h/week (<i>n</i> = 92) (%)	31.5	47.8	65.2	80.4	46.7	68.5
Driving > 7 h/week (<i>n</i> = 88) (%)	42.0	45.5	71.6	90.9	56.8	79.5
<i>z</i> -score	1.46	0.32	0.92	2.00	1.35	1.69
<i>p</i> -value	.143	.750	.358	.046	.176	.091
Roundabout ≤ 1 per week (<i>n</i> = 72) (%)	28.7	42.6	67.6	85.2	48.1	68.5
Roundabout > 1 per week (<i>n</i> = 108) (%)	47.2	52.8	68.1	86.1	56.9	80.6
<i>z</i> -score	2.65	1.37	0.06	0.13	1.17	1.62
<i>p</i> -value	.0080	.1697	.9511	.8930	.2430	.1046
Pedestrian ≤ 5 per week (<i>n</i> = 100) (%)	26.0	43.0	63.0	84.0	44.0	68.0
Pedestrian > 5 per week (<i>n</i> = 80) (%)	50.0	51.3	75.0	87.5	61.3	81.3
<i>z</i> -score	3.32	1.10	1.72	0.66	2.30	2.01
<i>p</i> -value	.0009	.2703	.0855	.5069	.0214	.0443

NOTE: Boldface entries indicate *p*-value < .05.

to yield to pedestrians. Results may further suggest that the effects of the tested treatments are independent of driver experience with roundabouts, as the two categories are found to have comparable yielding rates, on average. These results imply that the tested treatments will have a more significant relative effect on increasing the yielding rate for drivers with less roundabout experience.

Average Count of Passes Through Intersections with Pedestrian Crossings (Pedestrians)

Drivers who had a higher number of encounters with pedestrians in intersections tended to have higher yielding rates in roundabouts, across all scenarios. However, the difference was significant only in the base scenario and in the scenarios with RRFB installation. However, when a PHB was installed or the crosswalk was relocated, although the yielding rate increased for both categories of drivers, there was no significant difference between the two populations. Therefore, drivers with more weekly pedestrian encounters are likely to be more responsive to yielding to pedestrians with the existence of an RRFB signal. However, these results of the questionnaire were self-reported, and the possibility that some drivers did not know when they failed to notice pedestrians is not taken into account.

Eye Tracker Results

The critical performance measures of the eye tracker data are the frequency and duration of fixation, measured in milliseconds. The research team defined a threshold fixation duration, which was used to infer that the driver's visual attention was in fact focused on the object in question (pedestrian or beacon). The proper threshold for fixation duration found in the literature is 67 ms (0.067 s) (23). (For the purposes of this study the team used the same threshold.) Therefore, any fixation duration less than 0.067 s was eliminated from the data.

The results of this experiment can assist with understanding whether the drivers were aware of the presence of the beacons and pedestrians along the road and whether they comprehended the implication of their presence. Drivers essentially must negotiate

traffic from three different directions in the roundabout while their main focus is to drive out of the circulating lane toward the exit leg. Therefore, drivers will tend to pay less attention toward objects along the road or the sidewalk along the way.

Table 5 shows the results from the eye tracker experiments. For scenarios with no beacon installations, fixations on pedestrians were extracted and analyzed; and for scenarios with PHB and RRFB installations, fixations on pedestrians and beacons were extracted and analyzed. Because the RRFB system was modeled in the form of side-mounted beacons, it was not possible to do depth analysis with the eye tracker data and distinguish between fixation on the pedestrian and the RRFB. Therefore, for the RRFB the fixation was on pedestrians and the beacon. The PHBs were overhead beacons, and therefore fixations on pedestrians and the beacon could be distinguished in the analysis.

Results show that the number of fixations was highest in the PHB60 scenario at an average of 7.8 fixations, relative to the base case of 3.1. The result of a *t*-test on the difference between the number of fixations on the pedestrian in each scenario compared with the base scenario shows that installing any kind of beacon will significantly increase the number of fixations on the pedestrian or, in general, on the objects along the road. Therefore the presence of a beacon tended to increase drivers' attention to the presence of pedestrians in their path. For the PHB20 scenario, the increase in the number of fixations was not significant at the 95% confidence level. It is hypothesized that in the 20-ft scenario, the PHB was located too close to the roundabout and made it difficult for drivers to make eye contact. The comparative values of percent fixation on objects and fixation duration also support that hypothesis.

Relocating the crosswalk and stop bar to 60 ft did not produce a significant increase in the number of fixations on the pedestrian for the base case. For the RRFB and PHB treatments, the relocation of the crosswalk to 60 ft does suggest a slight increase in the number of fixations on the pedestrian over the equivalent 20-ft scenario, but these increases are not statistically significant. The *p*-values for 20 ft versus 60 ft for an RRFB and PHB are .306 and .101, respectively.

The *t*-test on the percentage of fixations on the pedestrian and both the pedestrian and RRFB in the scenarios shows the same trend observed in the number of fixations. Table 5 shows no significant

TABLE 5 Eye Tracker Results for Six Scenarios

Scenario	Object	Number of Fixations			% Fixation on Object			Fixation Duration (s)			<i>t</i> -Test ($\alpha = 0.05$)
		Average	SD	<i>t</i> -Test ($\alpha = 0.05$)	Average	SD	<i>t</i> -Test ($\alpha = 0.05$)	Average	SD	Max.	
CTRL20	Pedestrian	3.1	1.6	Base	8	6.40	Base	0.201	0.105	0.683	Base
CTRL60	Pedestrian	3.8	1.9	$p = .76$	10	6.30	$p = .82$	0.222	0.144	0.842	$p = .13$
RRFB20	Pedestrian & beacon	5.9	2.6	$p = .009$	32	5.80	$p = .030$	0.301	0.292	2.758	$p = .031$
RRFB60	Pedestrian & beacon	6.1	2.6	$p < .001$	65	7.20	$p < .001$	0.329	0.248	2.075	$p < .001$
PHB20	Pedestrian	5.4	2.4	$p = .057$	20	8.20	$p = .060$	0.242	0.276	2.518	$p = .051$
	Beacon	6.2	2.3	na	32	6.50	na	0.272	0.304	2.700	na
PHB60	Pedestrian	7.3	2.5	$p < .001$	26	6.10	$p = .022$	0.275	0.315	3.814	$p < .001$
	Beacon	7.8	2.3	na	51	7.30	na	0.385	0.345	5.375	na

NOTE: Boldface entries indicate p -value $< .05$; na = not applicable.

difference between the base scenario and CTRL60, but a more significant difference between the rest of the scenarios and the base case. At a 95% confidence level, there is no significant difference between the base case and PHB20, which suggests against installing a PHB close to roundabouts.

A t -test on the values of fixation durations shows that there was not a significant difference in the duration of drivers' fixations on pedestrians in the CTRL60 and base (CTRL20) scenarios. The t -test also supports the results of the number of fixations and percentage of fixations on pedestrians. Overall, the three measures of effectiveness listed in Table 5 suggest that the relocation of the crosswalk, by itself, did not produce a significant increase in drivers' gaze pattern on pedestrians. Although having an overhead PHB beacon 20 ft from the stop bar increased the fixation time, such placement was not significant at the 95% confidence level.

Table 6 shows the regression models developed for the eye tracker measures of effectiveness; x_1 , x_2 , and x_3 are binary factors (0 or 1), and they define the crosswalk relocation to 60 ft, presence of a PHB, and presence of an RRFB, respectively (when equal to 1). The coefficients show how much the measures of effectiveness (number of fixations, percentage of fixations on object, and fixation duration) will be changed with any of these conditions. Factors x_2 and x_3 cannot be equal to 1 at the same time.

Debriefing Questionnaire on Treatment Effectiveness

A series of debriefing questions was asked pertaining to drivers' experience with roundabouts and their perception of the different treatments installed in each of the scenarios. The results indicated that 91% of the subjects were aware of the presence of both types of beacons at the roundabout. This percentage means that 9% (or four

drivers) did not even notice the RRFB or PHB at the crosswalk. Nearly 80% of the drivers understood the purpose of both beacons at the roundabouts. However, about 9% of the drivers did not associate the PHBs with pedestrian crossings, and 11% of the drivers were seemingly unaware of the RRFB's purpose. Overall, 76% of the drivers felt safer with the stop bars located at 60 ft, whereas 7% did not notice the difference. The rest of the drivers (18%) felt that the stop bar should be moved even farther away from the roundabout.

Each driver was also asked to rank the perceived safety of each treatment scenario from 1 to 5, with 1 being the least safe and 5 being the safest condition, which will promote nearly 100% yielding to pedestrians. The results of the safety scores with each scenario and their 96% confidence level are shown in Figure 2. The results show that participants felt the safest with the PHB or RRFB, having stop bars located 60 ft downstream of the roundabout. The safety score of PHB60 is significantly higher than that of other scenarios; however, with respect to stop bars located at 20 ft from the roundabouts, drivers prefer to have an RRFB compared with an overhead PHB. One possible explanation is that with a stop bar at 20 ft, drivers do not feel safe enough to yield to pedestrians. Therefore they prefer to have an RRFB, which implies caution and does not show a red indication to stop. The RRFB gives the option to drivers (with yellow flashing lights) of whether to yield or not yield, whereas the solid red location at the PHB requires a driver to stop. The safety score of the base scenario (CTRL20) and crosswalk relocation scenario (CTRL60) are not significantly different.

CONCLUSION

This paper aimed to test three different pedestrian crosswalk treatments at the exit leg of multilane roundabouts by using a driving simulator and eye tracker. Six unique scenarios were developed

TABLE 6 Regression Models Developed for Eye Tracker Measures of Effectiveness

Regression Model	Intercept	Coefficient for x_1 (= 1 if crosswalk at 60 ft)	Coefficient for x_2 (= 1 if beacon is PHB)	Coefficient for x_3 (= 1 if beacon is RRFB)	R^2
Number of fixations	3.1	0.89	2.73	1.61	.56
% fixation on object	0.09	0.02	0.68	0.49	.43
Fixation duration	0.198	0.011	0.083	0.072	.51

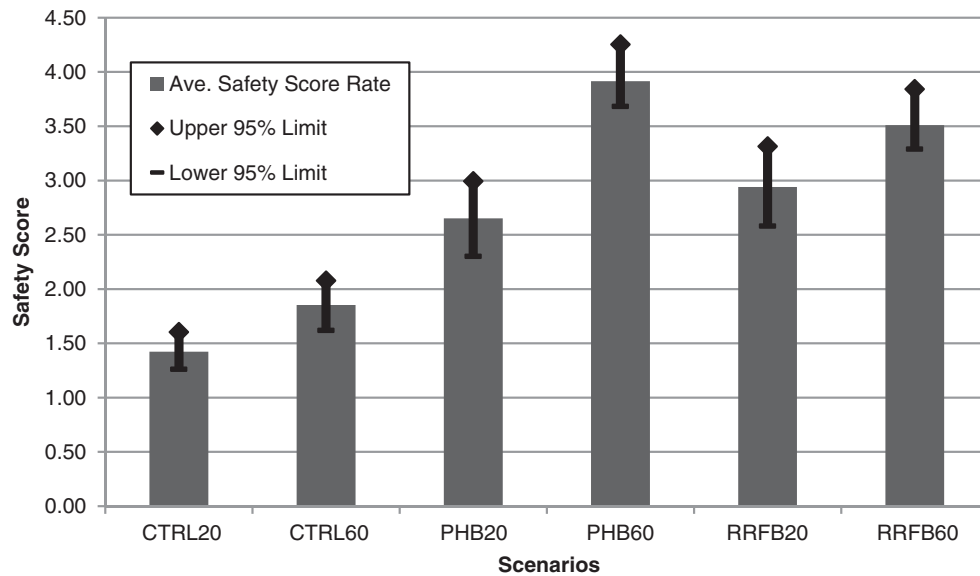


FIGURE 2 Driver safety score rate (ave. = average).

on the basis of the combination of crosswalk distance and type of beacon (or no beacon at all). The three treatments studied were the base scenario (CTRL), pedestrian hybrid beacon (PHB), and rectangular rapid flashing beacon (RRFB). Each treatment was tested by using two crosswalk locations (stop bars located at 20 and 60 ft). Drivers were asked to drive a simulated corridor of eight roundabouts, four of which had pedestrian crossings. The driver yielding rate to pedestrians in each scenario showed that the existence of any kind of beacon increases the driver yielding rate significantly ($\alpha = 0.05$). Among the treatment options, the use of the PHB signal with a stop bar located at 60 ft appeared to have the highest increase in the yielding rate.

Further analysis on the effect of subject population attributes shows some effects on the yielding rate. In general, longer driving experience has a significant effect on increasing the yielding rate when it comes to the installation of beacons as treatments. Other attributes, such as the average driving hours per week, average pedestrian encounters, or average weekly passes through roundabouts, do not show conclusive effects on increasing the propensity to yield.

The eye tracker provided valuable information about the gaze patterns of drivers while exiting the roundabouts. Three performance measures, including the number of fixations, the percentage of fixation on objects of interest, and mean fixation duration, were investigated. Overall, the existence of any type of beacon at a roundabout increased the drivers' attention to the pedestrians waiting to cross.

For future analysis, a more detailed study of the results of eye tracker data to analyze gaze pattern for each yielding or nonyielding event for drivers in different scenarios is planned. Future research will also explore the relationship between drivers' speed at exit and their yielding.

The findings in this research imply that the use of RRFB or PHB systems successfully increased the rate of driver yielding at the exit leg of multilane roundabouts. For both beacon treatments, the yield rate was further increased when the treatment was relocated to a distance of 60 ft, instead of the 20-foot standard crosswalk location. This low-cost modification to the crosswalk therefore warrants additional consideration, especially because it has been linked

in previous research to lower pedestrian-induced vehicular delay effects of the installed signal.

Finally, the yielding rate resulting from the PHB (with solid red indication) was significantly higher than that of the RRFB, which only has a flashing yellow beacon. Although care should be taken in drawing broad conclusions from this simulator to engineering practice, the yielding rate of only 85.6% is disconcerting. Even the highest yield percentage of 90.7% is well below the full compliance that one might expect from a solid red indication. This rate is comparable with findings at a field installation of a PHB at a two-lane roundabout, where red light running occurred 12.6% of the time (4), a rate which is actually quite similar to the 14.4% observed, and within the lower bound of the 95% confidence interval of 80.4% (19.6% noncompliance). The 85.6% average compliance rate furthermore is for the PHB60 location, whereas the rate for the more standard 20-ft crosswalk is only 68.3%. Although not statistically significant, the yielding rate at a 60-ft-distance RRFB was higher than for a 20-ft-distance PHB. These results call for a careful exploration of any future installations of PHBs or other beaconing systems at multilane roundabout exits, as some compliance issues are expected.

ACKNOWLEDGMENTS

The project described was supported by a grant from the National Eye Institute. The authors also thank all individuals who participated in the study, as well as the staff of the Institute for Transportation Research and Education (ITRE) and the Ergonomics Laboratory at North Carolina State University who helped with the driving simulator.

REFERENCES

1. U.S. Access Board. *Revised Draft Guidelines for Accessible Public Rights-of-Way*. <http://www.access-board.gov/prowac/draft.htm>. 2006. Accessed July 1, 2010.

2. Ashmead, D., D. Guth, R. Wall, R. Long, and P. Ponchillia. Street Crossing by Sighted and Blind Pedestrians at a Modern Roundabout. *ASCE Journal of Transportation Engineering*, Vol. 131, No. 11, Nov. 1, 2005, pp. 812–821.
3. Guth, D., D. Ashmead, R. Long, and P. Ponchillia. Blind and Sighted Pedestrians' Judgments of Gaps in Traffic at Roundabouts. *Human Factors*, Vol. 47, No. 2, 2005, pp. 314–342.
4. Institute of Transportation Research and Education. *NCHRP Report 674: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*. Transportation Research Board of the National Academies, Washington, D.C., 2011.
5. Access Board Research. *Pedestrian Access to Modern Roundabouts: Design and Operational Issues for Pedestrians Who Are Blind*. <http://www.access-board.gov/research/roundabouts/bulletin.htm>. Accessed May 5, 2011.
6. Geruschat, D. R., and S. E. Hassan. Driver Behavior in Yielding to Sighted and Blind Pedestrians at Roundabouts. *Journal of Visual Impairment and Blindness*, Vol. 99, No. 5, 2005, pp. 286–312.
7. Texas Transportation Institute. *NCHRP Report 562: Improving Pedestrian Safety at Unsignalized Crossings*. Transportation Research Board of the National Academies, Washington, D.C., 2006.
8. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *NCHRP Report 672: Roundabouts: An Informational Guide*, 2nd ed. Transportation Research Board of the National Academies, Washington, D.C., 2010.
9. U.S. Access Board. *Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Rights of Way*. Notice of Proposed Rulemaking. Released July 26, 2011. <http://www.access-board.gov/prowac/nprm.htm>. Accessed July 27, 2011.
10. *Manual on Uniform Traffic Control Devices (MUTCD)*. FHWA, U.S. Department of Transportation, 2009. http://mutcd.fhwa.dot.gov/kno_2009.htm. Accessed June 1, 2011.
11. Fitzpatrick, K., S. T. Chrysler, R. Van Houten, W. W. Hunter, and S. Turner. *Evaluation of Pedestrian and Bicycle Engineering Countermeasures: Rectangular Rapid-Flashing Beacons, HAWKs, Sharrows, Crosswalk Markings, and the Development of an Evaluation Methods Report*. Report No. FHWA-HRT-11-039. FHWA, U.S. Department of Transportation, 2011.
12. Fitzpatrick, K., and E. S. Park. *Safety Effectiveness of the HAWK Pedestrian Crossing Treatment*. Report No. FHWA-HRT-10-042. FHWA, U.S. Department of Transportation, 2010.
13. Hunter, W., R. Srinivasan, and C. A. Martel. *Evaluation of the Rectangular Rapid Flashing Beacon at a Pinellas Trail Crossing in St. Petersburg, Florida*. Final report. Florida Department of Transportation, Tallahassee, 2009.
14. Shurbutt, J., and R. Van Houten. *Effects of Yellow Rectangular Rapid-Flashing Beacons on Yielding at Multilane Uncontrolled Crosswalks*. Report No. FHWA-HRT-10-043. Final report. FHWA, U.S. Department of Transportation, 2010.
15. Shurbutt, J., and R. Van Houten. *TechBrief: Effects of Yellow Rectangular Rapid-Flashing Beacons on Yielding at Multilane Uncontrolled Crosswalks*. Report No. FHWA-HRT-10-046. FHWA, U.S. Department of Transportation, 2010.
16. Ergonomics Lab, North Carolina State University. <http://www.ise.ncsu.edu/ergolab/equipments/>. Accessed May 11, 2011.
17. Zhang, Y., and D. Kaber. An Empirical Assessment of Driver Motivation, Emotional Response and Driving Conditions on Risk-Taking Decisions. Presented at 3rd International Conference on Applied Human Factors and Ergonomics, Miami, Fla., July 2010.
18. Montgomery, D. C. *Design and Analysis of Experiments*, 6th ed. John Wiley and Sons, Inc., Hoboken, N.J., 2005.
19. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter. *NCHRP Report 572: Roundabouts in the United States*. Transportation Research Board of the National Academies, Washington, D.C., 2007.
20. Fleiss, J. L., A. Tytun, and H. K. Ury. A Simple Approximation for Calculating Sample Sizes for Comparing Independent Proportions. *Biometrics*, Vol. 34, 1980, pp. 343–346.
21. Duchowski, A. T. *Eye Tracking Methodology: Theory and Practice*, 2nd ed. Springer-Verlag London Limited, London, 2007.
22. Schroeder, B. J., N. M. Roupail, and R. G. Hughes. Toward Roundabout Accessibility—Exploring the Operational Impact of Pedestrian Signalization Options at Modern Roundabouts. *ASCE Journal of Transportation Engineering*, Vol. 134, No. 6, 2008, pp. 262–271.
23. Geruschat, D. R., S. E. Hassan, and K. A. Turano. Gaze Behavior While Crossing Complex Intersections. *Optometry and Vision Science*, Vol. 80, No. 7, 2003, pp. 515–528.

The contents of this paper are the responsibility of the authors and do not necessarily represent the official views of the National Eye Institute or the National Institutes of Health.

The Roundabouts Task Force peer-reviewed this paper.