Investigating Driver Yielding Behavior at Roundabout Approaches

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ABSTRACT

A survey was conducted with 463 participants to investigate the effect of pavement marking configurations at roundabout approaches on yielding behavior. Participants were asked to indicate where they would yield in an overhead view, given four different pavement marking configurations in a dynamic portion of the survey. Statistical comparisons found the distributions of yielding locations differ significantly. “Shark teeth” pavement marking resulted in participants yielding five feet further upstream than scenarios without. “YIELD” alone had the greatest variance, while “shark teeth” pavement markings result in the smallest variance in yield locations. Demographics, roundabout understanding, and whether drivers thought roundabouts provided a safety benefit did not result in different driver yielding locations. The results suggest drivers yield in different locations depending on different pavement marking configurations at roundabout approaches, which may influence the number of rear-end collisions. These findings can help impact future pavement marking application decisions.

INTRODUCTION

Roundabouts have been found to reduce fatal and injury crashes significantly when compared with other types of intersection traffic control (Bill et al., 2011; Elvik, 2003; FHWA, 2009a; Garder, 1998; Khan et al., 2013; Persaud et al., 2001; Retting et al., 2001; Rodegerdts et al., 2007; Rodegerdts et al., 2010). Therefore, roundabouts are a Federal Highway Administration (FHWA) endorsed countermeasure to reduce the severity and frequency of intersection related crashes (FHWA, 2009a). Wisconsin has installed 329 roundabouts as of 2015 with roundabouts located in all regions of the state, and over 400 planned by the end of 2017. A study of the Wisconsin roundabouts found fatal and injury crashes decreased by 38% (Kahn et al., 2013); however total crashes increased, driven by an increase in property-damage-only crashes.

Public perception of roundabouts can suffer as a result of the high frequency of property-damage-only crashes, causing some motorists to believe roundabouts are unsafe. Savolainen et al. conducted a survey in Michigan and found nearly 40% of respondents viewed roundabouts unfavorably, and favorable opinions decreased with participant age (Savolainen et al., 2012). Improving design to make roundabouts as intuitive as possible is one way to reduce the frequency of low severity crashes that occur at roundabouts.

Roundabout design reduces the occurrence of the most severe crash types, such as head-on, left-turn related, and angle crashes. However, these design characteristics come at a trade-off as other less severe crash types (e.g., rear-end collisions) increase. In an examination of rear-end collisions in Wisconsin, one factor found to impact the rear-end crash frequency was the pavement markings at roundabout approaches (Burdett et al., 2016), specifically the "shark teeth" pavement marking and the word "YIELD" (shown in Figure 1). The impact of the pavement markings on rear-end collisions may be due to differences in driver understanding about where to yield on an approach to a roundabout, given the various configurations of pavement markings a driver may have previously encountered at various roundabouts.

Figure 1. Pavement marking examples.

To determine if pavement markings affect driver understanding about where to yield at roundabout approaches, a driver survey was conducted in the Madison, Wisconsin area. The survey studied driver behavior and comprehension through an interactive, dynamic survey to determine the drivers' understanding of where to yield given different pavement marking configurations. The results can help incorporate driver behaviors and opinions with respect to pavement markings into future design decisions as well as in developing driver educational programs for roundabouts.

BACKGROUND

Rear-End Crashes

Rear-end crashes have been found to be one of the most frequently occurring crash types at roundabouts. Rear-end crashes historically account for between 15% and 31% of all roundabout crashes (Arndt & Troutbeck, 1998; Burdett et al., 2016; Mandavilli et al., 2009; Rodegerdts et al., 2007), and 17% of fatal and injury crashes at roundabouts (Rodegerdts et al., 2007). Rodegerts et al. (2007) also found a higher occurrence of rear-end crashes at single-lane roundabouts compared to multi-lane roundabouts. Rear-end crashes have been found to be affected by age, with younger drivers more likely to be involved in crashes and the risk decreasing with age (Burdett et al., 2016; Singh, 2003). Many rear-end collisions have been found to be the result of a driver miscalculating the time required to brake to avoid collision (Kuge et al., 1995). An examination of rear-end collisions found that at single-lane roundabouts the word "YIELD" was associated with a lower number of rear-end collisions (Burdett et al., 2016). At multi-lane roundabouts, the "shark teeth" pavement markings were associated with higher expected crashes.

Roundabout Approach Pavement Markings

Pavement markings play an important role in guiding drivers and other road users. Pavement markings, along with signing and roadway geometry, attempt to make navigating a roundabout as intuitive as possible. Transverse pavement markings are used at roundabout approaches to provide pedestrian facilities, as well as give supplemental information to drivers (e.g., lane-use arrows, route selection information, and yield markings). A sample approach is shown in Figure 2 illustrating the placement of the pedestrian crosswalk, "shark's teeth" (referred to as "White Yield Line" in the MUTCD), the word "YIELD", and the white entrance line. While the entrance line is nearly ubiquitous at roundabouts in the United States, the other pavement markings are placed on an as-needed basis at the discretion of the roundabout designers and as per road agency policy.

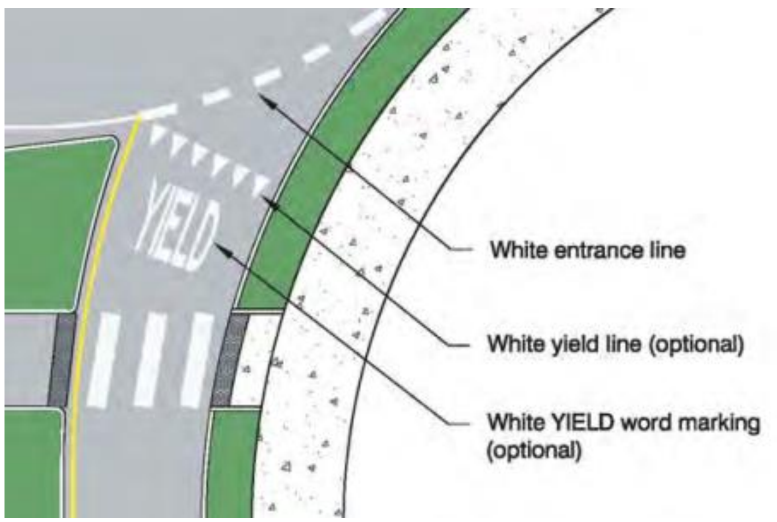


Figure 2. Sample intersection layout (Rodegerdts et al., 2010).

The wide dotted entrance line is an extension of the edge line of the circulatory road representing the separation between entering and circulatory traffic. The MUTCD Section 3C.03 suggests that these pavement markings should be placed across the entry lanes to roundabouts (FHWA, 2009b*)*. Additionally, there are two optional yield pavement markings in the MUTCD used at roundabout approaches. The word "YIELD" is an optional pavement marking that should be used in situations where drivers may need additional information about the upcoming need to yield. The word "YIELD" is particularly recommended in the event of frequently observed failures to yield at a roundabout entrance (Rodegerdts et al., 2010). In Wisconsin, this marking is mainly used as an educational tool when a roundabout is first installed (Wisconsin DOT, 2015). The word "YIELD" is primarily used on multi-lane roundabouts with the pavement marking placed in each approach lane. However, the marking could be used in the case of unique geometry or locations with frequent yield violations.

"Shark's teeth" markings are another optional marking. The MUTCD Section 3B.16 describes the "shark's teeth" as a series of isosceles triangles pointing toward the approaching vehicles (FHWA, 2009b*)*. According to the MUTCD Section 3C.04, "Shark's teeth" "may be used to indicate the point behind which vehicles are required to yield at the entrance to a roundabout" (FHWA, 2009b*)*. These lines should be placed perpendicular to the roadway. In the case of multi-lane roundabouts, they should be staggered to give drivers appropriate lines of sight.

Pavement Markings & Driver Behavior

Research specific to driver comprehension of roundabout pavement markings is limited. Roundabouts are an intersection that may violate driver expectancies, making the correct conveyance of information paramount. Text painted on roadways has proven effective in certain situations since drivers tend to scan the roadway directly in front of their vehicle (Chrysler & Schrock, 2005). When supplemental pavement markings exist, the need for a driver to divert their gaze for a significant amount of time is negated. In general, pavement markings have been found to be effective at speed reduction on roadways (Corkle et al., 2001; Hallmark et al., 2007). Advance yield markings ("shark's teeth") have been found effective at increasing the likelihood a driver yields at mid-block crossings (Fisher & Garay-Vega, 2012; Gomez et al., 2011).

METHODS

Survey Design

The survey was designed to investigate drivers' understanding of where to yield at roundabout approaches given different pavement marking configurations. In addition, questions were asked regarding demographics and roundabout opinions. Only participants with a valid driver's license or driver permit were surveyed at five locations. Survey participants were primarily from two DMV locations. To ensure a large enough younger (18-24) and older (65 and older) driver sample, surveys were also collected at a student union and two senior centers, respectively. Due to the need to present a dynamic illustration of vehicles traversing the roundabout, tablet PCs were used to administer the survey through a web-based survey tool. Participants were free to ask questions, although the intent of the survey was never conveyed to the participants while they were completing the survey. Given that yield locations were the primary objective of the survey, only questions pertaining to the yielding locations were required by the survey participants. If demographic or roundabout opinion questions were missing the survey was still considered complete and therefore included in the yield location analysis.

Yielding Locations

The survey's primary objective was to determine how drivers perceive the message the pavement markings convey. The pavement markings in the survey were conveyed through an overhead view, which may be a limitation as drivers usually interact with pavement markings from the perspective of a vehicle. Two pavement markings were examined: "shark teeth" pavement markings and the word "YIELD." A full factorial design was employed to examine each possible combination for a total of four different pavement marking configurations (shown in Figure 3). The different configurations were presented to the survey participants with the instructions to select where they would yield before entering the roundabout. The four yield location questions were dynamic, presented as videos, with two moving vehicles: one vehicle on the approach and one navigating the circulating lanes. All videos were the same except the varying pavement marking configurations. The purpose of the vehicle in the circulating lane was to make clear to participants they would need to yield at the roundabout approach before entering the circulating lanes. The video would playback the sequence of images showing the movement of both vehicles for a few seconds. The vehicle on the approach would not "drive" far enough along the approach to lead the survey participant to believe the final approach vehicle position was the correct yield location and then reset to the original location. Each of the yield location questions was presented in a random order to the participants to ensure there was no learning effect. The participants were told they could click multiple times until satisfied with the selected yield location, and only the final response would be recorded.

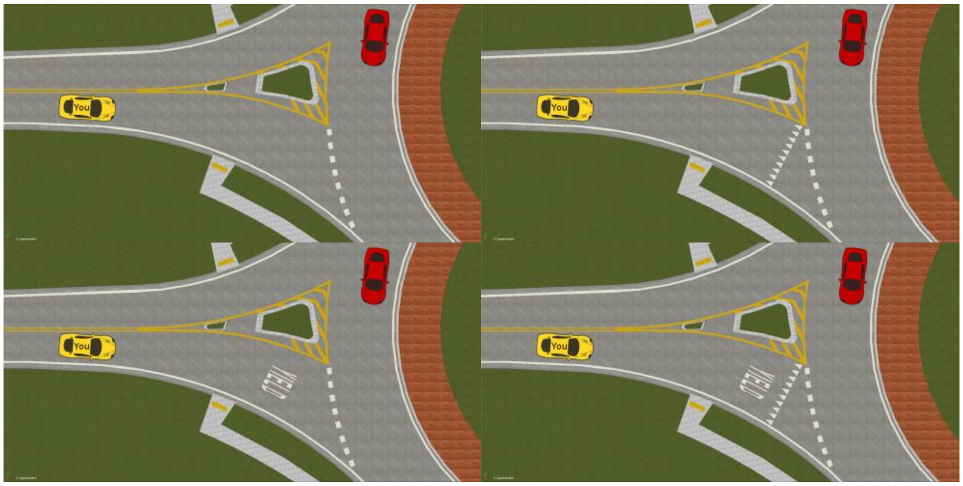


Figure 3. Four yield location configurations.

Data Processing

From each participant's response, x- and y-coordinates were recorded for each yielding scenario. Apparent outliers that were not on the roadway in the direction of travel were removed from the dataset, including any yielding locations within the circulating or exit lanes of the roundabout, as well as points located in the grass. The plots of raw data for each of the eight scenarios after eliminating outliers are shown in Figure 4.

Since the focus was the longitudinal differences in driver yielding locations all survey participant yield locations were collapsed to a single axis along the centerline of the roadway perpendicular to the participant's chosen x-, y-coordinate yielding location. This simplification was deemed appropriate given the inherent error from survey participants clicking their yield location on the tablet. Once the yielding locations were collapsed to the centerline axis, distributions of participant yield locations were plotted for each pavement marking scenario. From these distributions, yield locations greater than 1.5 times the Interquartile Range (IQR) were removed from further analysis.

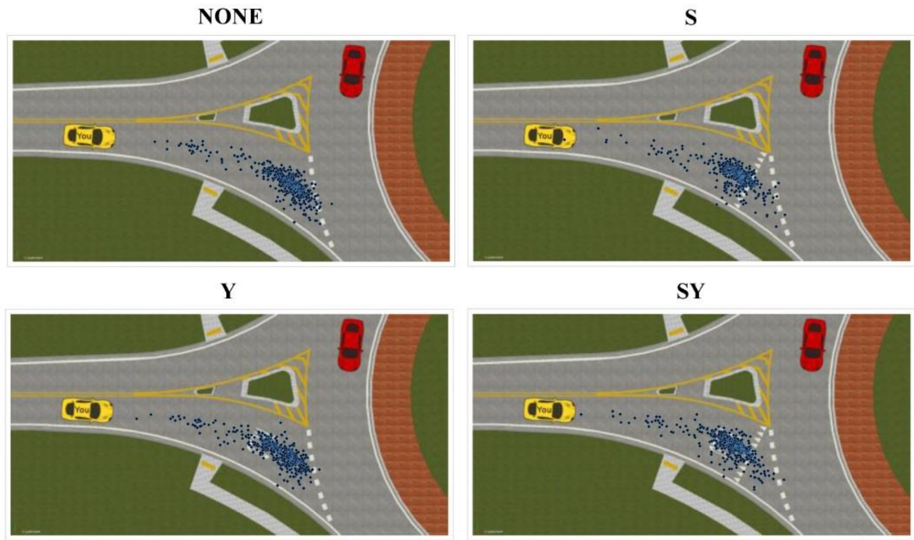
Data Analysis

Once the outliers were removed the final distributions were created for each pavement marking configuration. Table 1 shows the sample sizes used in the yield location analysis after the removal of outliers.

From the distributions, the scenarios were compared to determine whether they were significantly different from each other. No assumption was made regarding the underlying distributions of the data. The non-parametric Kolmogorov-Smirnov (KS) (shown in Equation 1) test was employed to determine if the distributions were statistically different.

$$D_{n,m} = \sup_x | F_{1,n}(x) - F_{2,m}(x) | \quad (1)$$

Where $D_{n,m}$ is the test statistic between two distributions F_1 and F_2, $\sup_x$ is the supremum function, $F_{1,n}(x)$ and $F_{2,m}(x)$ are the empirical distribution functions from the first and second test distributions, respectively.



Note:

None: No Supplemental Pavement Marking (Only Entrance Line)
S: "Shark teeth" Pavement Marking
Y: "YIELD" Pavement Marking

Figure 4. Participant yield location raw data.

Table 1. Yielding location sample sizes.

Pavement Marking Configuration	Sample Size
NONE (Edge line only)	424
S	413
Y	427
SY	420

Six KS-test pairwise comparisons were conducted between each scenario. Given that six pairwise comparisons were conducted for each pavement marking configuration a Bonferroni correction was used, changing the rejection level for the KS-test to $\alpha = 0.05/6 = 0.008833$. The null hypothesis is rejected at level α if the test statistic, $D_{n,m}$, is greater than the inequality shown in Equation 2.

$$D_{n,m} > \sqrt{-\frac{1}{2}\ln\left(\frac{\alpha}{2}\right)\left(\frac{n+m}{nm}\right)} \quad (2)$$

Where n and m are the sample sizes of the first and second distributions, respectively.

Further, to compare the data the ANOVA test was conducted on the data. While the distribution of the data was not known, we assumed the data to be normally distributed for the purposes of the ANOVA test.

In addition, yield locations for different demographic groups were compared to determine if there was any difference among groups. Three demographics relevant to driver understanding of roundabouts were tested. The three demographics compared were age, whether roundabouts were covered in the driver's education program, and whether the driver believes roundabouts provide a safety benefit compared to other traffic control types.

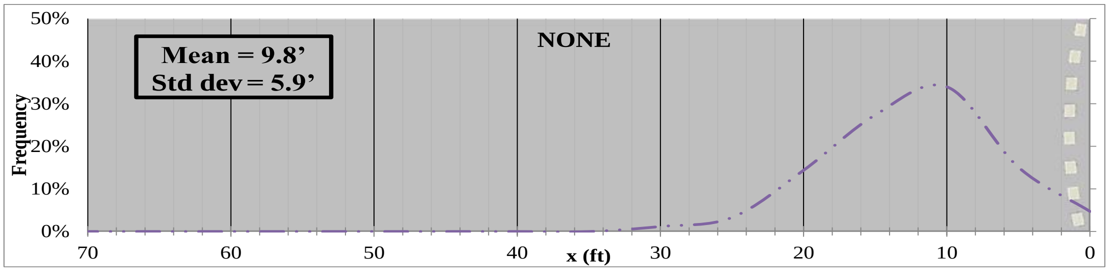
Table 2. Survey demographics and general roundabout opinion results.

Survey Demographics

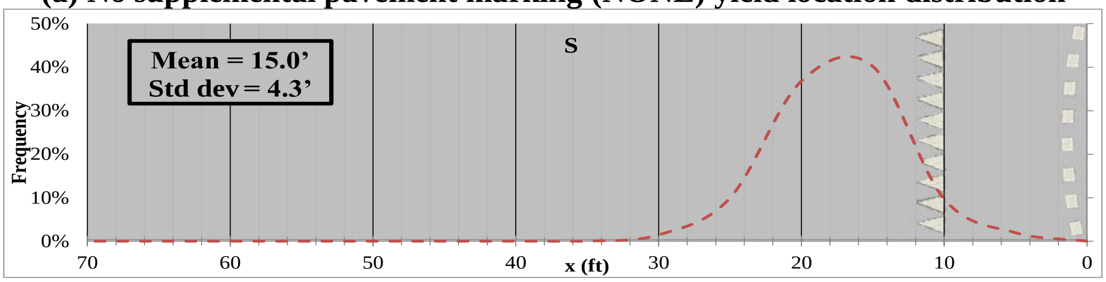
Category	Count	%	Category	Count	%
Age			Education		
18-24	100	21.8%	High School Diploma or Less	57	12.5%
25-44	179	39.0%	Some College	108	23.6%
45-64	131	28.5%	2 Year Degree	42	9.2%
65+	49	10.7%	4 Year Degree	137	29.9%
Total	459	100.0%	Professional/Master's Degree	91	19.9%
Hours spent driving per week			Doctorate	23	5.0%
Less than 5	154	33.9%	Total	458	100.0%
5 to 10	126	27.7%	Time since driver's education program		
11 to 20	88	19.3%	0-5 years ago	83	18.3%
21 to 30	63	13.9%	5-10 years ago	69	15.2%
More than 30	24	5.3%	10-20 years ago	96	21.2%
Total	455	100.00%	20-40 years ago	124	27.4%
Gender			More than 40 years ago	81	17.9%
Male	236	51.8%	Total	453	100.0%
Female	219	48.0%			
Prefer Not to Answer	1	0.2%			
Total	456	100.0%			

General Roundabout Opinion Results

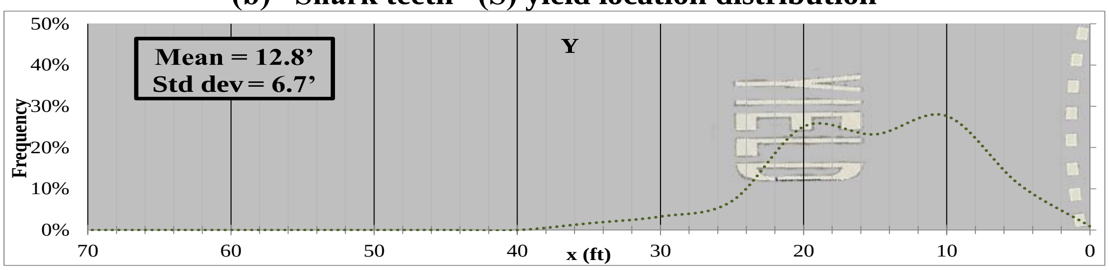
Category	Count	%	Category	Count	%
Driver's education program cover roundabouts?			Understand how to navigate a roundabout		
Yes	144	32.0%	Strongly Agree	207	46.0%
No	306	68.0%	Agree	183	40.5%
Total	450	100.0%	Neutral	37	6.9%
Have you driven through a roundabout before?			Disagree	12	2.8%
Yes	429	96.2%	Strongly Disagree	5	0.8%
No	17	3.8%	Total	444	100.0%
Total	446	100.0%	Roundabouts provide a safety benefit		
If so, how frequently?			Strongly Agree	97	22.0%
1 or 2 since licensed driver	12	2.8%	Agree	129	29.3%
Few times a year	59	14.0%	Neutral	116	26.3%
Few times a month	116	27.4%	Disagree	73	16.6%
Few times a week	148	35.0%	Strongly Disagree	26	5.9%
Every Commute	88	20.8%	Total	441	100.0%
Total	423	100.0%	Roundabouts provide an operational benefit		
			Strongly Agree	148	32.9%
			Agree	178	43.0%
			Neutral	78	17.6%
			Disagree	25	5.8%
			Strongly Disagree	7	1.4%
			Total	436	100.0%



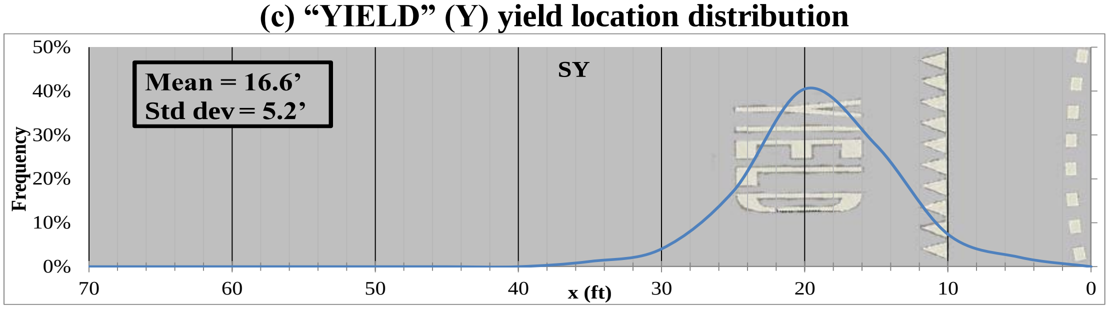
(a) No supplemental pavement marking (NONE) yield location distribution



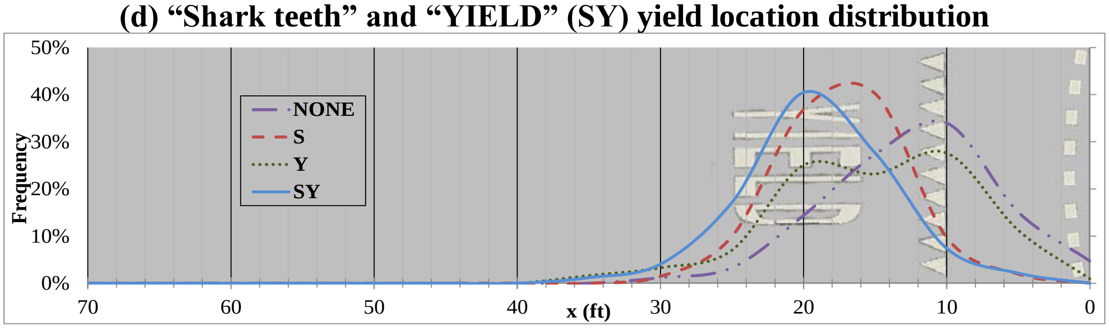
(b) “Shark teeth” (S) yield location distribution



(c) “YIELD” (Y) yield location distribution



(d) “Shark teeth” and “YIELD” (SY) yield location distribution



(e) Combined yield locations

Figure 5. Yielding distributions of scenarios.

RESULTS & DISCUSSION

Demographics

Basic demographic questions were asked to determine the participants' age, gender, education, hours spent driving a week, and the number of years that have elapsed since their driver's education program. The demographics of the survey participants are shown in Table 2. Overall, 463 participants completed some portion of the demographic and roundabout opinion questions, along with the yield specific questions. The spread of male and female participants was fairly even (51.8% to 48.0%, respectively). Age groups were broken up according to census age groupings. A good representation of different age groups was obtained. Drivers over the age of 65, represent 10.7% of the sample, while drivers in the age group 18-24 represent 21.8%.

Nearly two-thirds of participants had not learned about roundabouts in their driver's education program. However, this was strongly correlated to the participant's age. In Wisconsin, roundabouts have been included in driver's education for less than a decade, so younger drivers were much more likely to be exposed to roundabouts in driver's education programs. Around 76.5% of drivers aged 18 to 24 covered roundabouts in their driver's education programs, while two of the drivers over 65 had. Overwhelmingly, most participants (96.2%) had driven through a roundabout. Over half (55.8%) of the participants who had driven through a roundabout did so more than once a week.

Participants overwhelmingly believed they understood how to navigate a roundabout. Nearly 86.5% of participants thought they understood how to navigate a roundabout, while only 3.6% believed they did not understand how to navigate. Participants views of the safety benefits of roundabouts were more mixed. Just over half (51.3%) of participants believed roundabouts provided a safety benefit compared to stop signs or traffic signals, while 22.5% believed roundabouts were less safe than stop- and signal-controlled intersections. When considering the operational benefits of a roundabout, participants were less divided. About 76% of participants believed roundabouts had an operational benefit when compared to stop- and signal-controlled intersections, with only 7.2% believing stop- and signal-controlled intersections were better operationally.

Participant Yield Location Analysis

The distributions of the four different scenarios were each compared. The distributions for the scenarios can be seen in Figure 5.

Table 3. K-S test statistical results.

Comparison Results	D	p-value
NONE (9.8') v. S (15.0')	0.4615	<0.0001*
NONE (9.8') v. Y (12.8')	0.2068	<0.0001*
NONE (9.8') v. SY (16.6')	0.5287	<0.0001*
S (15.0') v. Y (12.8')	0.2946	<0.0001*
S (15.0') v. SY (16.6')	0.1468	0.0003*
Y (12.8') v. SY (16.6')	0.3446	<0.0001*

*Denotes significance at $\alpha = 0.008833$ level

In general, scenarios were unimodal upstream from the entrance line to the roundabout. The KS-test statistic results for the scenarios can be seen in Table 3. The mean yielding distances for each pavement marking configuration are shown in parentheses.

The results of the six pairwise KS-tests with the Bonferroni corrections found all scenarios were significantly different from each other clearly illustrating the impact pavement markings have on drivers' understanding of where to yield on the approach to a roundabout. Further, results from ANOVA were also found to be significant (p-value < 2e-16). When the "shark teeth" pavement marking was present, drivers chose to yield approximately five feet further back than if the "shark teeth" were not present. Additionally, in scenarios with the word "YIELD" standard deviations were larger than scenarios without the word "YIELD," particularly for scenarios where only the word "YIELD" was present. Demographic testing results of the yielding locations did not yield significant results across the different demographics for the four pavement marking configurations.

CONCLUSIONS

Past research has found pavement markings at roundabout approaches have an impact on the expected number of rear-end collisions, specifically, the "shark teeth" pavement marking, and the word "YIELD." One hypothesis is the effect pavement markings have on roundabout approach-related rear-end collisions may be due to differences in driver understanding of where they need to yield. To investigate this hypothesis, a driver survey was conducted at five locations in the Madison, Wisconsin area.

In total, 463 surveys were completed. The results found that most drivers had not learned about roundabouts in their driver's education programs. This result was strongly correlated to age, with over three-quarters of younger drivers (18-24) having learned how to navigate roundabouts and nearly none of the senior drivers (65 and older). However, nearly all participants had driven through a roundabout, and over half did so at least once a week. Regardless of a driver's familiarity with roundabouts, drivers overwhelmingly believed they understood how to navigate a roundabout. Just over half of participants thought roundabouts provided a safety benefit, although over three-quarters of participants believed roundabouts had operational benefits.

Concerning drivers understanding of yielding locations, two different pavement markings were tested: "shark teeth" pavement markings and the word "YIELD." A complete factorial design resulted in four scenarios which were randomly presented to the drivers. At scenarios with the "shark teeth" pavement marking participants chose to yield approximately five feet further back from the entrance line than when this pavement marking was not present. The word "YIELD" caused a larger variance amongst participant yield locations. The results suggest the supplemental pavement markings ("shark teeth" and "YIELD") do impact driver yielding behavior at roundabout approaches. Drivers have clear differences in understanding about where they should yield given different pavement marking configurations. The results suggest supplemental pavement markings at roundabout approaches are not intuitive to drivers. Supplemental markings should be taught in drivers' education programs, so drivers understand the messages the supplemental pavement markings convey.

This research takes a preliminary look at quantifying the message these pavement markings convey to drivers from one region in Wisconsin. The results could be bolstered in the future by extending the survey to other regions, or even other states where roundabouts are not as prevalent. While the results of the study do suggest pavement markings have an impact on yield location, the results do not suggest which pavement marking combinations provide drivers with an intuitive message. Future research should examine driver's understanding of pavement markings at other locations in the United States as well as at multilane roundabouts. Additionally, a field study will enable examination of actual driving behavior while a full-scale driving simulator study will provide more accurate insight into driver behavior regarding pavement markings while also controlling for various geometric characteristics.

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