TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Research Article

Transportation Research Record
2019, Vol. 2673(8) 397–407

DOI: 10.1177/0361198119843093
journals.sagepub.com/home/trr
SAGE

Evaluation of Driver Comprehension and Visual Attention of the Flashing Yellow Arrow Display for Permissive Right Turns

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Abstract

This research explored driver comprehension and behaviors in Oregon with respect to right-turn signal displays focusing on the Flashing Yellow Arrow (FYA) in a driving simulator. A counterbalanced, factorial design was chosen to explore three independent variables: signal indication type and active display, length of the right-turn bay, and presence of pedestrians. Driver decision-making and visual attention were considered. Data were obtained from 46 participants (21 women, 25 men) turning right 736 times in 16 experimental scenarios. A Mixed-effects Ordered Probit Model and a Linear mixed model were used to examine the influence of driver demographics on observed performance. Results suggest that the FYA indication improves driver comprehension and behavioral responses to the permissive right-turn condition. When presented with the FYA indication in the presence of pedestrians, nearly all drivers exhibited caution while turning and yielding to pedestrians and stopping when necessary. For the same turning maneuver, drivers presented with a circular green (CG) indication were less likely to exhibit correct behavior. At least for Oregon drivers, another clear finding was a general lack of understanding of the steady red arrow (SRA) display for right turns. Most drivers assume the SRA indication requires a different response than the circular red (CR) and remain stopped during the entire red interval, thus resulting in efficiency losses. These findings suggest that transportation agencies could potentially improve driver yielding behavior and pedestrian safety at signalized intersections with high volumes of permissive right turns from exclusive right-turn lanes by using the FYA display in lieu of a steady CG display.

Accommodating motor vehicles that are turning (left or right) at signalized intersections requires careful consideration of the safety and efficiency trade-offs related to geometric and operational variables. Turning vehicle phases can be operated as protected or permissive intervals, or in a combination of these modes (i.e., protected/permissive) in a leading or lagging sequence. For protected intervals, the turning movement is given the exclusive right-of-way and no conflicts with other users exist. For permissive intervals, drivers must search for acceptable gaps in the conflicting traffic (vehicular and non-motorized) and complete the turning maneuver. The National Highway Traffic Safety Administration (NHTSA) reports that in 2016, 18% of pedestrian fatalities occurred at intersections (*1*). Turning vehicles are the primary collision risk for non-motorized road users.

Through traffic and right-turning traffic tend to operate at different speeds and can potentially cause safety issues in a shared lane configuration. Speed differentials in a shared lane can result in increased delay for through vehicles and increased likelihood of rear-end crashes (*2*). To mitigate this problem, use of an exclusive right-turn lane may be appropriate (*3*). Exclusive right-turn lanes improve safety and have the potential to improve the overall operation and efficiency of an intersection (*3*).

For left-turns, all modes of operation are common. In selecting the appropriate operation, traffic engineers consider pedestrian volumes, vehicle volumes of turning and opposing traffic, speeds, sight distance, time-of-day demands, and other factors. In general, while protected operation usually increases driver inconvenience (delay), research indicates the protected operation is safer (*4*). For right turns, permissive operation is the default and nearly universal unless geometry, demand, or other

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circumstances require protected operation (usually timed as an overlap). Practically, this means that most right turns are permitted during the pedestrian walk and clearance indications and yielding issues often arise. In addition, right turn on red is allowed unless signed, and drivers turning right on red often do not come to complete stop setting up conflicts with pedestrians. The options for right-turn operation are further muddied by the fact that the appropriate response to the steady red arrow (SRA) (either stop and stay stopped, or stop and proceed when a gap is present) is not consistent in state vehicle codes (*5*). Pedestrian and right-turning vehicle crashes can be mitigated by restrictions on right turn on red, exclusive pedestrian intervals, and leading or lagging pedestrian intervals (*6–8*). Geometric modifications such as tight corner radii, curb extensions, and pedestrian safety islands all force drivers to navigate intersections more cautiously and can improve safety for pedestrians (*9*).

An important component of safe permissive operation is proper driver response to traffic control. For permissive left-turn operations, a substantial and compelling body of research has established that the flashing yellow arrow (FYA) improves driver comprehension and yielding in response to conflicting movements. This research, spanning nearly 20 years, examined driver behaviors and comprehension and explored five different permissive left-turning signal indications in three configurations (*10–13*). This comprehensive work, involving surveys, focus groups, human factors testing, and driving simulators, resulted in the FYA being incorporated in the Manual on Uniform Traffic Control Devices (MUTCD). Interestingly, while the FYA indication is also allowed for permissive and protected/permissive right-turn operations in the MUTCD, there is no existing literature on driver comprehension or behavior related to the FYA indication for right turns.

The objective of this research was to explore driver comprehension and behaviors with respect to the various right-turn signal displays, with a focus on the FYA indication. This paper describes the results of experiments in a driving simulator that was part of a larger study that included an internet-based comprehension survey and software-in-the-loop simulations (*14*). This simulator experiment evaluated drivers' observed and recorded behaviors as well as analysis of the glance duration data. The results suggest improved driver decision-making in the permissive operation of FYA as compared with the circular green (CG) indication and generally poor comprehension of the SRA indication for right turns. The subjects were all Oregon drivers where FYA is common for left-turn operations and the vehicle code requires the same driver response to the circular red (CR) as the SRA indication.

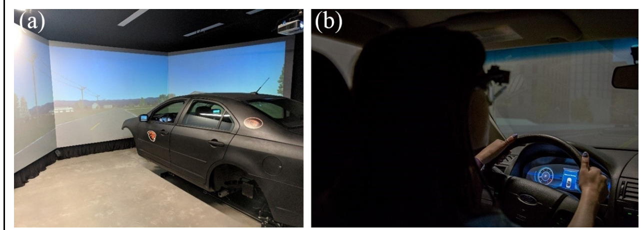

Figure 1. Views from (*a*) outside OSU driving simulator and (*b*) inside the OSU driving simulator.

Data and Methods

This research was conducted in the full-scale Oregon State University (OSU) driving simulator. The simulator, virtual environment, experimental design, subject recruitment, data acquisition, and coding of the observed driver behavior is described in this section.

Driving Simulator

The OSU driving simulator is a high-fidelity motion-based simulator comprising a full 2009 Ford Fusion cab mounted above an electric pitch motion system capable of rotating ±4° (see Figure 1). The vehicle cab is mounted on the pitch motion system, with the driver's eye point located at the center of the viewing volume. The pitch motion system allows for the accurate representation of acceleration or deceleration (*15*). Three liquid crystals on silicon projectors with a resolution of 1,400 by 1,050 are used to project a front view of 180° by 40°. These front screens measure 11 ft by 7.5 ft. A digital light-processing projector is used to display a rear image for the driver's center mirror. The two side mirrors have embedded liquid crystal displays (LCDs). The update rate for projected graphics is 60 Hz. Ambient sounds around and internal sounds in the vehicle are modeled with a surround-sound system. The computer system includes a quad-core host running Realtime Technologies SimCreator Software (version 3.2) with a 60-Hz graphics update rate. Finally, the driving simulator is also equipped with SimObserver (version 2.02.4), which has five cameras positioned at various viewing angles to observe the actions of participants when approaching an intersection.

Virtual Environment

The virtual environment was developed by using Simulator software packages, including Internet Scene Assembler (ISA) (version 2.0), SimCreator, and Blender (version 2.71). The simulated test track was developed in ISA by using JavaScript-based sensors that change the signal indication and display dynamic objects, such as

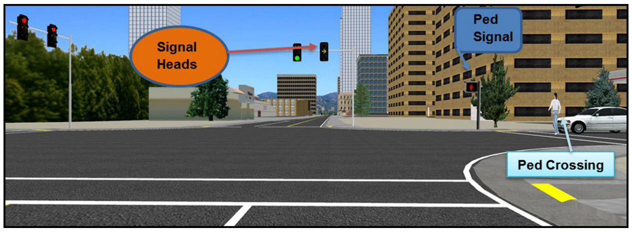

Figure 2. Example of signal and pedestrian head configurations in the simulator environment.

pedestrians crossing in the conflicting crosswalk of the right-turning participant vehicle.

Intersection approaches included one through lane and an exclusive right-turn lane, along with a single receiving lane for the right-turn movement. The posted speed limit was 35 mph, land use was light-to-medium-density commercial and industrial development, and light ambient traffic was included. The roadway cross-section consisted of two 12-ft traffic lanes in each direction with no median, while the cross-section of the roadway receiving the right-turn roadway consisted of two 10-ft traffic lanes in each direction with no median. A yellow centerline, solid white edge line, small 1-ft paved shoulder, and 6.5-ft-wide pedestrian sidewalks on both sides of the road were constantly present. Traffic signal heads and a pedestrian signal head indication (with either the walking person or upraised hand background) were created for use in the simulator scenarios. Figure 2 provides an example of both signal heads as seen in the simulator from the perspective of an approaching driver.

Experimental Design

A factorial design was chosen for this experiment to enable exploration of the interactions between the independent variables. Three independent variables are included in the experiment: 1) right-turn signal indication which has 4 levels (CR, SRA, CG, and FYA); 2) two levels of pedestrian presence in the conflicting crosswalk (one pedestrian crossing and no pedestrian); and 3) two levels of turning bay length (50 ft and 100 ft). Figure 3 provides an example of the two levels of turning bay length and presence of pedestrian.

The factorial design for the three independent variables resulted in the inclusion of 4 × 2 × 2 scenarios, which were presented within subjects. To control for practice effects, the order of right-turn grid presentation was counterbalanced and the placement of each scenario on each grid was randomly assigned (*16*, *17*). Thus, four different track layouts were developed and presented in random order to each participant. Each track had four right-turning maneuvers, and each right turn was randomly assigned one level for each of the three independent variables, and start and finish locations of these grids were varied.

Once the vehicle entered the exclusive right-turning bay, there was a proximity sensor that was triggered and the pedestrian started moving northbound. The scenario was designed so that the approaching vehicle would be about to turn and the position of pedestrian would be in the middle of the crosswalk in the receiving lane. This was calculated based on the vehicle speed and the turning bay length.

Subject Recruitment

A total of 52 individuals (25 women, 27 men), primarily from the community surrounding Corvallis, Oregon, were participants in the experiment. The subjects were limited to licensed drivers residing in Oregon with at least 1 year of driving experience. Recruitment efforts were made to distribute the participants in the sample evenly by gender. Approximately 10% of the subjects (3 women, 2 men) reported simulator sickness and did not complete the experiment. All responses from participants who exhibited simulator sickness were excluded from the analyzed data set. Failure to calibrate the experimental equipment accurately resulted in the loss of data for one additional participant. The final analyzed sample comprised 46 participants with an average age of 30.91 years (SD = 11.85) who completed the experiment (note that only 43 had complete eye-tracking data). The subjects included 21 women (age μ = 29.3, SD = 11.8 years) and 25 men (age μ = 32.3, SD = 11.7 years). Table 1 summarizes the demographic information of the subjects.

Data Acquisition

After the motorists' eyes were calibrated to the driving simulator screens, subjects completed a 5-min calibration drive to acclimate participants to the mechanics of the vehicle and the virtual environment of the simulator. If they did not exhibit signs of simulator sickness, subjects were instructed to begin the experiment. Subjects were instructed to turn right, left, or drive through the intersection by an automated voice command set to announce twice at 400- and 200-ft in advance of the intersection. Figure 4 shows an example grid layout with four right-turning scenarios (there were six tracks to drive).

Two primary dependent variables were extracted from the simulator data. First, driver decision-making was observed by driver behavior (stop, yield, or go) in response to the signal display and phasing. Second, visual attention was recorded from the eye-tracking equipment as participants glanced towards a signal

Figure 3. Example scenarios of right turns with 100-ft (top left) and 50-ft (top right) turning bay length, with a pedestrian (bottom left) and without a pedestrian (bottom right).

indication. Drivers' behavior and vehicle response data were collected from the driving simulator and *SimObserver* platform during the experiment. A complete data file was generated for each participant for each of the six experimental drives. A total of 107 hours of video and vehicle characteristics (e.g., lateral position and velocity) were recorded. These were coded as described in the following section.

In conjunction with the driving simulator, an eye-tracking system was used to record where participants were looking while driving in the simulator. Eye-tracking data were collected with the ASL Mobile Eye-XG platform, which allows the user unconstrained eye and head movements. A 30-Hz sampling rate was used, with an accuracy of 0.5–1.0°. Gaze was calculated based on the correlation between the participant's pupil position and the reflection of three infrared lights on the eyeball. The ASL Mobile Eye-XG system records a fixation when the participant's eyes pause in a certain area of interest (AOI) for more than 100 ms. Figure 5 shows a visualization of the tracking software.

After collecting participants' eye-movement data, fixation and dwell data were analyzed by AOI polygons with the *ETAnalysis* software suite. For this process, researchers watched each video segment that included a right turn at an intersection (16 per participant). These video segments were cropped to the length of time that the driver entered the turning bay (generally 10–30 s). Researchers drew AOI polygons on individual video frames in a sequence separated by intervals of approximately 5–10 frames. The *ETAnalysis* software calculated the fixation data on each AOI. The motorist's eye-tracking data started from the point when the participant entered the turning bay at the intersection and continued until the participant completed the right-turn maneuver.

Table 1. Participant Demographics

Possible responses	Number of participants	Mean	SD
Gender			
Male	25	0.54	0.50
Female	21	0.46	0.50
Age			
Age	46	30.91	11.85
Race			
White or Caucasian	35	0.76	0.43
Black/African American	1	0.02	0.15
Hispanic/Latino	3	0.06	0.25
Asian	5	0.11	0.31
Other	2	0.04	0.20
Income			
Less than $25,000	23	0.50	0.50
$25,000 to less than $50,000	4	0.09	0.28
$50,000 to less than $75,000	3	0.06	0.24
$75,000 to less than $100,000	6	0.13	0.34
$100,000 to less than $200,000	7	0.15	0.36
$200,000 or more	1	0.02	0.14
Prefer not to answer	2	0.04	0.20
Education			
High School diploma or GED	1	0.02	0.15
Four-year degree	6	0.13	0.34
Some college	16	0.35	0.48
Master's degree	16	0.35	0.48
PhD degree	5	0.11	0.31
Associate degree	2	0.04	0.20
How many miles did you drive last year?			
0–5,000 mi	15	0.32	0.47
5,000–10,000 mi	12	0.26	0.44
10,000–15,000 mi	9	0.19	0.40
15,000–20,000 mi	8	0.17	0.38
More than 20,000 mi	2	0.05	0.20

Coding of Driver Behavioral Responses

A complete data file was generated for each participant. Files, including collected video data and all output of vehicle characteristics (e.g., lateral position and velocity), were opened in the Data Distillery (version 1.34) software suite, which provided quantitative outputs (numerical and graphical) in combination with the recorded video. Figure 6 shows the video output in conjunction with numerical data (right side) and graphical representations of data in columns (bottom). Each right-turning maneuver was carefully reviewed and classified into three categories: correct response was given a comprehension score of 100, partially correct response was given 50, and an incorrect response was given 0, based on established criteria shown in Table 2.

For the CG action, to be coded as correct, participants must turn right after yielding to pedestrians (if present) in the crosswalk. Partially correct actions resulted from

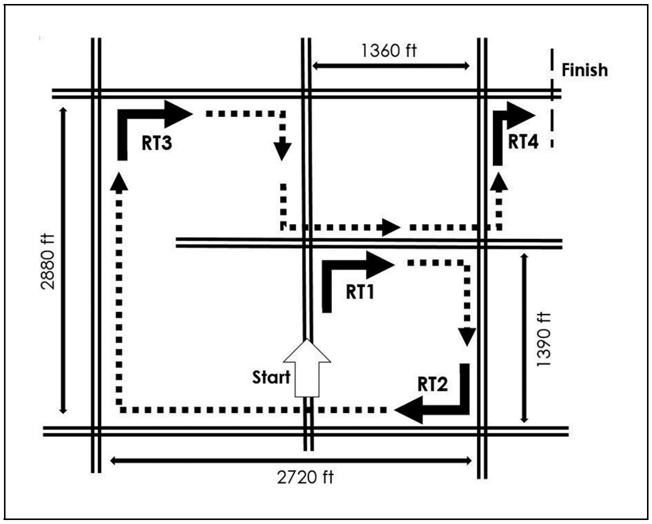

Figure 4. Example layout of the grid with four right-turning (RT) scenarios.

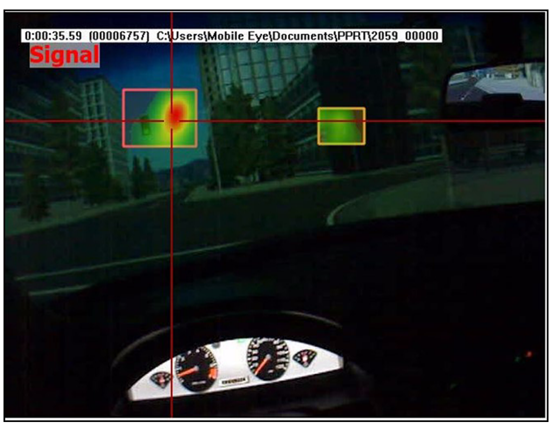

Figure 5. Example of a participant fixation pattern on the signal indication head.

drivers turning right without checking for pedestrians even though the walk indication was displayed, or not checking before turning but stopping once they saw a pedestrian. Incorrect actions resulted from either driver coming to a complete stop (vehicle speed < 1 mph) to check for pedestrians, or a crash with a pedestrian. The coding convention followed for CR and SRA indications was the same, as according to Oregon law the expected correct action for both display indications is the same for right turns. Responses were classified as correct if participants came to a complete stop (vehicle speed < 1 mph) and completed the turn when a safe gap was selected. Partially correct actions resulted from drivers making the right turn without coming to a complete stop. Responses were coded as incorrect if participants came to a complete stop and waited for a green indication. For the FYA indication, driver responses were coded as correct if they exhibited caution while turning and yielded to pedestrians when present, stopping when necessary. Partially correct actions resulted from drivers not turning right with caution (vehicle speed > 15 mph) or not yielding when necessary. Responses were coded as incorrect if drivers came to a complete stop (vehicle speed < 1 mph) before turning, or if they remained stopped until the signal display became green.

Results

Two measures of driver performance were evaluated: comprehension score and visual attention. Throughout the analysis, the CG and FYA indications that require drivers to yield and the CR and SRA indications that require drivers to stop are compared. Data were analyzed and visualized in Minitab software for Windows (version 18.1), JMP software (version 14.0.1), and STATA (version 14).

Driver Comprehension

Descriptive Analysis. Table 3 shows the frequency distribution for the three comprehension scores at each level of each independent variable. As shown in the table, participants turning right on the FYA indication had the highest correct comprehension score based on the observed behavior in the simulator. The correct comprehension scores are higher in the presence of pedestrian with bay length of both measurement 50 ft and 100 ft which both reported the highest frequency count (45 out of 46). The CG display had comparable comprehension scores in the absence of a pedestrian (34 and 35) but the scores across the choices remained nearly the same in the presence of a pedestrian. In the review of the data, many near-misses with pedestrians were observed during the CG indication. This suggests that the FYA display improves driver response to the permissive nature of the movement (i.e., they recognize the need to check for conflicts). The SRA indication resulted in the most variable and lowest score for driver response. Participants turning right on SRA indication without the presence of a pedestrian in an exclusive 50 ft bay length reported the highest frequency of incorrect comprehension scores (32 out of 46). This poor comprehension is likely related to the fact that, although the signal displays (CR and SRA) have the same legal interpretation in Oregon, drivers seem to interpret the SRA as requiring something different. Many drivers assume the SRA indication requires them to stay stopped until a green indication is displayed. The highest incorrect comprehension score for the CR indication is possibly a carry-over effect since drivers were presented with both CR and SRA displays in the same track.

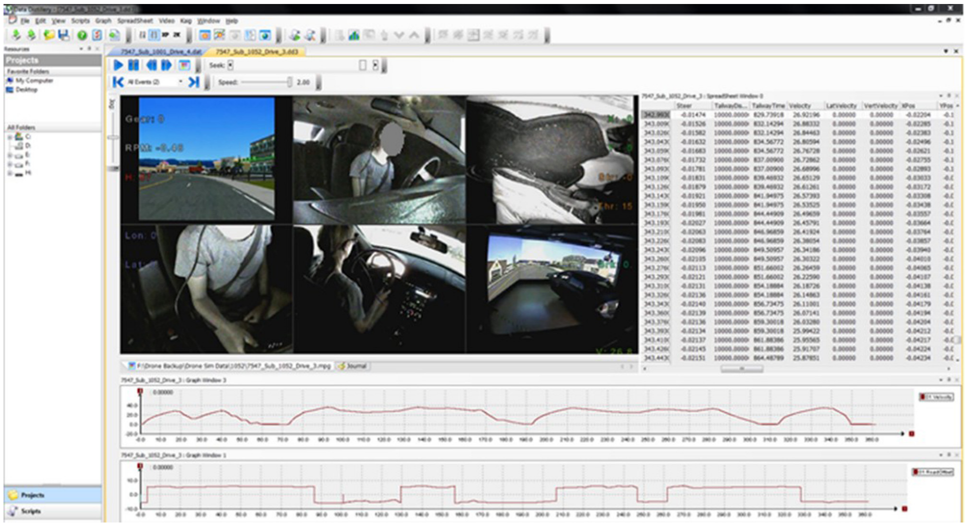

Figure 6. Screenshot of Data Distillery software (identifiable participant information removed).

Table 2. Error Coding of Narrative for the Simulator Experiments

Display indication	Correct	Partially correct	Incorrect
Circular Green (CG)	Turn right with caution after yielding to pedestrians (if present) in the crosswalk	Turn right without checking for pedestrians even though the walk indication was displayed (or) not checking before turning but stopping once they saw a pedestrian	Stop before turning (vehicle speed < 1 mph) to check for pedestrians (or) A crash with pedestrian
Circular Red and Steady Red Arrow (CR and SRA)	Come to a complete stop (vehicle speed < 1 mph) and complete the turn when they find a safe gap	Turn right without coming to a complete stop (vehicle speed > 1 mph)	Stop and remain stopped until the green indication
Flashing Yellow Arrow (FYA)	Turn right with caution after yielding to pedestrians (if present) in crosswalk	Turn right without caution (vehicle speed > 15 mph) (or) not yielding when necessary	Stop before turning (vehicle speed < 1 mph) to check for pedestrians (or) remain stopped until the green indication

Table 3. Frequency of Comprehension Score

		Bay length 50 ft		Bay length 100 ft	
Signal indication	Descriptive statistics	Ped	No Ped	Ped	No Ped
Circular Red (CR)	Choices	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)
	Frequency (46)	(13, 10, 23)	(14, 3, 29)	(14, 3, 29)	(12, 10, 24)
Steady Red Arrow (SRA)	Choices	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)
	Frequency (46)	(31, 1, 14)	(32, 3, 11)	(31, 0, 15)	(30, 4, 12)
Circular Green (CG)	Choices	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)
	Frequency (46)	(3, 12, 31)	(3, 9, 34)	(6, 6, 34)	(5, 6, 35)
Flashing Yellow Arrow (FYA)	Choices	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)	(0, 50, 100)
	Frequency (46)	(0, 1, 45)	(7, 0, 39)	(0, 1, 45)	(5, 0, 41)

Mixed-Effects Ordered Probit Modeling. As the level of comprehension score (0, 50, and 100) is ordinal in nature, and to account for potential observed and unobserved heterogeneities in the data, a Mixed-effects Ordered Probit Model (MOP) was selected. To further examine driver performance, this approach with the subject as a

Table 4. Summary of Estimated Models of Comprehension Score Choices

Model	Variable	Levels	Estimate	SE	*p*-value
CR and SRA	Subject random effect (SD)		2.97	0.99	–
	Cut (1)	–	1.48	0.47	0.002
	Cut (2)		2.00	0.48	<0.001
	Signal indication	CR	1.92	0.35	<0.001
		SRA	Base Value	–	–
	Experience	C.	0.05	0.025	0.046
Summary statistics					
Wald X^2 (8)	75.35 ($P > X^2 = 0.00$)	Observations			368
Log Likelihood	–237.86 (–344.27 at (0))	Subjects			46
LR test (X^2bar) (*1*)	147.62 ($P > X^2bar = 0.00$)	Observation/subject			8
CG and FYA	Subject random effect (SD)		0.13	0.10	–
	Cut 1	–	–2.69	0.45	<0.001
	Cut 2	–	–2.16	0.46	<0.001
	Signal indication	CG	–1.49	0.48	0.002
		FYA	Base Value	–	–
	Signal x Ped	CG X PED	–1.04	0.57	0.07
			Base Value	–	–
Summary statistics					
Wald X^2 (7)	22.15 ($P > X^2 = 0.002$)	Observations			368
Log Likelihood	–196.70 (–214.26 at (0))	Subjects			46
LR test (X^2bar) (*1*)	2.85 ($P > X^2bar = 0.04$)	Observation/subject			8

Note: PED or Ped = pedestrian present; CG = circular green; C. = continuous variable.

random effect was developed to consider the treatment factors collected: signal types, bay length, and presence of a pedestrian. Driver demographics including: driver age, gender, level of education, race, income, vehicle type, number of years as a licensed driver, number of times driven in a week, and number of miles driven in the previous year were included in the model. The descriptive summary of these variables is shown in Table 1. A MOP model was chosen for analysis because 1) of its ability to handle the errors generated from repeated subject variable as the participants are exposed to all scenarios, 2) ability to handle fixed or random effects, 3) categorical and continuous variables can easily be accommodated, and 4) probability of Type I error occurring is low. Pearson's correlation coefficient was used to identify any correlated variables. In the case of statistically significant effects, pairwise comparisons of margins were adopted. All tests were performed at a 95% confidence level. Log Likelihood estimates were used in the final iteration.

Prior to modeling, a correlation analysis was completed. Specific variables, such as the number of years licensed, and how many times the participants drove in a week, were excluded from the model because they were highly correlated with age ($p < 0.001$) and number of miles driven in the previous year ($p < 0.001$) respectively. Vehicle type also was excluded because it was correlated with the variables decribing how many times the participants drove in a week and the miles driven in the previous year ($p < 0.001$). The remaining variables were explored using a stepwise procedure with the objective to select significant and exclude insignificant variables from the final models. However, the treatment factors and their interactions were always forced to be included in the model. Table 4 presents the final variables in the models. As the effect of independent variables on the intermediate category is hard to capture, predictive marginal effects are considered to assess the importance of individual parameters.

In the final MOP model for the stop indications (CR and SRA), the signal indication treatment is the only significant main effect on the driver comprehension score. The significant Likelihood-ratio test (147.62, $p < 0.001$) implies that the random effect model should be preferred to the fixed effects model. According to the marginal effects, the predicted probability of responding incorrectly is 0.65 if a driver encounters SRA and 0.34 otherwise. Out of the six driver demographics considered, only driver experience emerged as significant. Regardless of the other variables, with a one year increase in experience, there is an increased likelihood of drivers responding correctly, potentially indicating a positive association between years of driving experience with correct comprehension of the signal displays for right turns.

None of the treatment interaction (two- and three-way) effects were significant. However, they were considered in the pairwise comparison of margins for signal indication, bay length, and presence of a pedestrian. Figure 7 plots the percent of comprehension score at each level of signal indication, bay length, and presence of a pedestrian for the three response outcomes. Regardless of bay length, participants had a significantly higher correct comprehension score while encountering CR than SRA indication for scenarios with

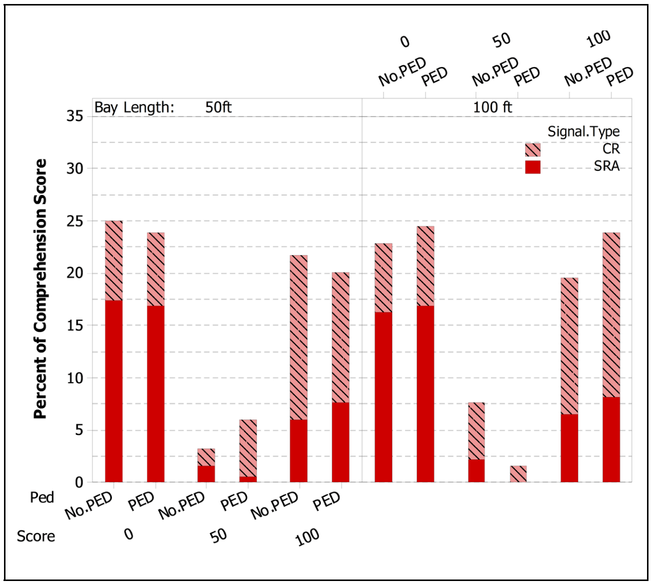

Figure 7. Three-way interactions on comprehension score for CR and RA indications.

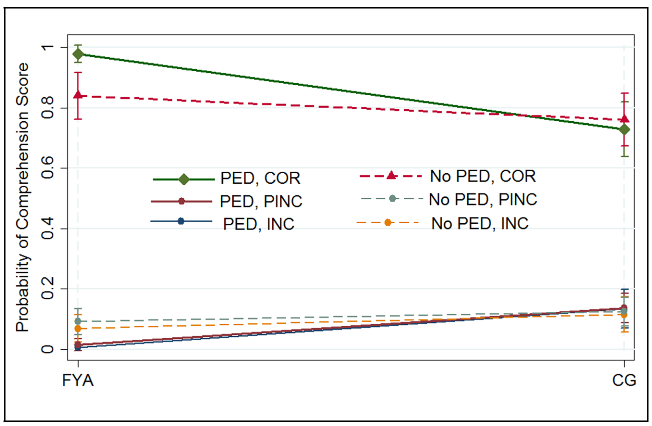

Figure 8. Two-way interactions on predictive probability of comprehension score for CG and FYA indications in presence of pedestrian.

and without a pedestrian present ($p < 0.001$). Pairwise comparison of marginal results revealed higher correct comprehension score for participants encountering CR than SRA indication for both bay length measurements while holding the presence of pedestrian factor as constant ($p < 0.001$). Finally, regardless the signal type, statistically significant differences were not observed for the three outcomes of comprehension scores (0, 50, and 100) with and without the presence of a pedestrian for both 50 ft and 100 ft bay lengths ($p > 0.05$).

The MOP model for the yield indications (CG and FYA) found that the signal indication treatment is the only significant main effect on driver mean comprehension score, out of all the treatment factors that were considered. The random effect was also significant (LR-test = 2.85, $p = 0.04$). According to the marginal effects, the predicted probability of responding correctly is 0.95 if a driver encounters FYA and 0.74 when CG. None of the six driver demographic variables considered were statistically significant. MOP revealed one statistically meaningful two-way interaction. All treatment factors were inspected by pairwise comparison of margins. Figure 8 plots the predictive marginal effects probability of comprehension score for each level of signal indication, and presence of a pedestrian. There was a statistically significant interaction between the signal indication and presence of a pedestrian on probability of comprehension score (Figure 8). When encountering an FYA indication, participants respond correctly with a probability of 0.98 in the presence of a pedestrian, and 0.72 when encountering CG.

Visual Attention

Descriptive Analysis. For each right-turning maneuver, the number and duration (in seconds) of participants' fixations on AOI were recorded, with a Total Fixation Duration (TFD) of 0 s indicating that the participant did not look at the target. The Average Total Fixation Duration (ATFD) was calculated by averaging all participants' total fixations using an AOI. Table 5 shows the mean (μ) and standard deviation (SD) values for TFD for each level of every independent variable. As shown in the table, participants turning right on FYA indication had the highest average comprehension score. For the CR and SRA comparison, mean TFDs ranged from 1.60 to 4.98 s. The highest mean TFD occurred with the SRA indication in the 50-ft bay when a pedestrian was not present. The lowest mean TFD occurred with the CR indication in the 50-ft bay when a pedestrian was not present. The increased duration of visual attention on the SRA indication, when considered in conjunction with the lower correct response rate observed in the driver decision-making, supports the connection between visual attention and cognition while driving (e.g., drivers looked at the SRA indication longer because they were unsure of what the correct response was, and many responded incorrectly).

Similarly, the mean TFD on the signal head was significantly higher when drivers were turning right on the FYA display than when they were turning right on a CR indication. Regardless of the length of the turning bay and presence of pedestrian, mean TFDs ranged from 0.47 to 2.14 s. The FYA indication in the 50-ft bay when a pedestrian was present had the highest mean TFD, and the CG indication in the 50-ft bay when a pedestrian was not present had the lowest mean TFD.

Linear Mixed Modeling (LMM). A modeling approach similar to the one that was followed for the comprehension score was used to statistically examine differences in

Table 5. Descriptive Statistics of Average Total Fixation Duration (Secs)

Signal indication	Descriptive statistics	Bay length 50 ft		Bay length 100 ft	
		Ped	No Ped	Ped	No Ped
Circular Red (CR)	M	1.78	1.60	2.02	1.93
	(SD)	(1.72)	(1.50)	(1.99)	(1.78)
Steady Red Arrow (SRA)	M	3.02	4.98	2.97	3.99
	(SD)	(2.06)	(3.82)	(1.95)	(3.11)
Circular Green(CG)	M	0.55	0.47	0.56	0.63
	(SD)	(0.66)	(0.42)	(0.10)	(0.56)
Flashing Yellow Arrow (FYA)	M	2.14	1.66	2.03	1.46
	(SD)	(1.67)	(0.16)	(1.56)	(0.74)

Note: M = mean.

Table 6. Summary of Estimated Models of Average TFD

Model	Variables	Levels	Estimate	DF	*p*-value
CR and SRA	Subject random effect (SD)	–	1.15	–	0.001
	Constant	–	3.45	41	<0.001
	Signal indication	CR	–0.95	294	<0.001
		RA	Base Value	–	–
	Presence of pedestrian	NO PED	0.34	294	0.002
		PED	Base Value	–	–
	Age	–	1.29	41	0.008
	Signal x Ped	CR X NO PED	–0.40	294	<0.001
		CR X PED	Base Value	–	–
Summary Statistics					
R^2	0.48	Observations			344
–2Log Likelihood	1515.60	Subjects			43
AIC	1522.45	Observation/subject			8
CG and FYA	Subject random effect (SD)	–	0.36	–	0.009
	Constant	–	1.16	38	<0.001
	Signal indication	CG	–0.63	294	<0.001
		FYA	Base Value	–	–
	Presence of pedestrian	NO PED	–0.12	294	0.011
		PED	Base Value	–	–
	Miles driven in previous year	10,001–15,000 mi	–0.34	38	0.032
		More than 20,000 mi	Base Value	–	–
	Signal x Ped	CG X NO PED	0.12	294	0.010
		CG X PED	Base Value	–	–
Summary Statistics					
R^2	0.46	Observations			344
–2Log Likelihood	989.09	Subjects			46
AIC	989.25	Observation/subject			8

Note: PED or Ped = pedestrian present; No Ped = no pedestrian present; CG = circular green.

mean TFD. The results of the model are shown in Table 6. The LMM models for the stop indications (CR and SRA) and yield indications (CG and FYA) found that the signal indication and presence of pedestrian are statistically significant but not for the bay length treatment. The random effect was significant for both models (Wald Z = 3.28, p = 0.001) and (Wald Z = 2.36, p = 0.009) respectively. On average, participants encountering SRA and FYA indications are spending a longer time (about 2 s) observing the display ($p < 0.001$) while turning right. This is in part owing to the fact that drivers assumed the SRA indication required them to stop and stay stopped until green response and were present longer in the turning bay.

Out of the six driver demographics considered, age was statistically significant (p = 0.008) in the stop indications model. A one year increase in participant age increases mean TFD on the CR and SRA by 1.29 s. For the yield indications model, only the miles that the subject drove in the previous year emerged as a significant factor. Regardless of the signal indication (CG or FYA), the mean TFD decreases by 0.34 s as the number of miles

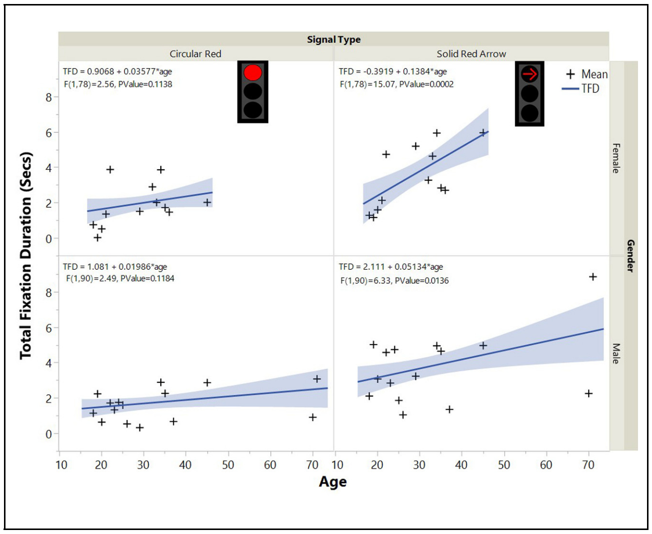

Figure 9. Distribution of mean TFD and age across stop signal displays by gender.

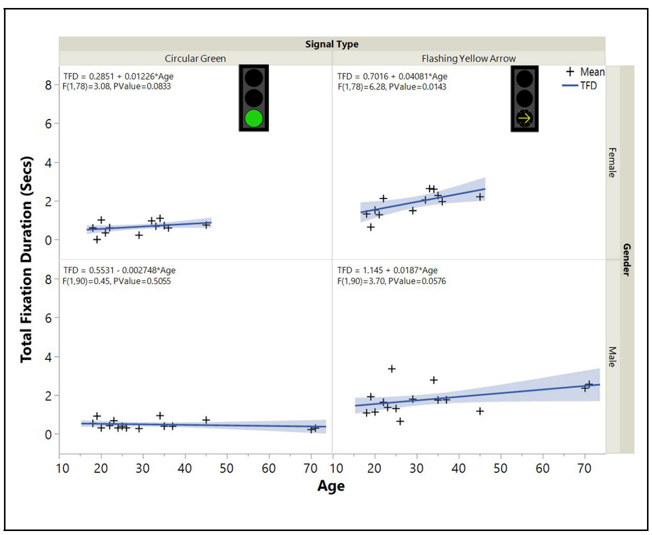

Figure 10. Distribution of mean TFD and age across yield signal displays by gender.

driven in the previous year drops to 15,00–20,000 mi when compared with more than 20,000 mi. The LMM model revealed one statistically meaningful two-way interaction for both models. All treatment factors were inspected by pairwise comparison. There was a statistically significant interaction between the signal indication and presence of pedestrian on mean TFD ($p < 0.001$). When encountering SRA indication, participants had fixated longer (1.5 s) when there was no pedestrian waiting to cross ($p < 0.001$). Moreover, when encountering FYA indication, participants fixated longer on the signal display (0.5 s) when there was a pedestrian crossing the street ($p < 0.001$).

To further explore the influence of age and gender on driver visual attention for each signal indication, Figure 9 depicts TFD in relation to age for participants. The shading represents the confidence interval of the prediction and the ' + ' symbol indicates the individual observations. Regardless of gender, the mean TFD for SRA indication has a strong positive relationship ($p < 0.05$) with age. Older drivers irrespective of gender tend to spend more time fixating on SRA indication. For both genders, strong correlations were not observed between mean TFD and age for CR indication.

The influence of age and gender on driver visual attention to yield signal indication was also investigated. Figure 10 depicts TFD in relation to participant age. Mean TFD for FYA indication has a strong positive relationship ($p < 0.05$) for female drivers. It is noteworthy, however, that association between mean TFD and age is almost significant ($p = 0.057$) for male drivers. As the drivers get older, irrespective of gender, they tend to spend more time fixating on the signal display before executing the right turn. For both genders, strong correlations were not observed between mean TFD and age for CG indication. There is a negative association between mean TFD and age for male drivers.

Conclusion

This paper examined driver comprehension and behaviors with respect to various right-turn signal displays with a focus on the FYA in a driving simulator. A counterbalanced factorial design experiment was conducted in the simulator to explore driver comprehension and visual attention using three independent variables: signal indication type and active display, length of the right-turn bay, and presence of pedestrians. Using data from 46 participants, MOP and LMM were used to study the impacts of demographics on observed driver performance when faced with four right-turn signal display alternatives. In summary, the results of this simulator experiment suggest that the FYA indication improves driver comprehension and behavioral responses to the permissive right-turn condition. When presented with the FYA and in the presence of pedestrians, nearly all drivers exhibited caution while turning and yielding to pedestrians when present, stopping when necessary. Both in the descriptive data and in the modeling, for the same turning maneuver, drivers presented a CG were less likely to exhibit correct behavior. While most drivers responded correctly to both the CG and FYA signals, drivers fixated on the FYA head longer. The longer duration, when considered in the context of the search for an acceptable gap, indicates a more robust visual search task (*18*). Another clear finding of this research was the general lack of understanding of the SRA displays for right turns (at least for Oregon drivers). Most drivers assume the SRA requires a different response than the CR and therefore remain stopped during the entire red interval. The LMM analysis found that driving experience contributed to comprehension and that drivers had better comprehension of the CR display. Like the FYA display, drivers tended to fixate longer on the SRA. Finally, older drivers, irrespective of gender, tend to spend more time fixating on the SRA indication. Though the comprehension error is fail-safe, given the variety of state vehicle codes, this is likely an issue in other states.

In relation to practice, the results suggest that transportation agencies could potentially improve driver yielding behavior and pedestrian safety at signalized intersections with exclusive right-turn lanes and separate right-turn signal heads by using the FYA display in lieu of a CG display. The use of the FYA in protected/permissive operation is also a clear application. This research is limited by the fact the work was done in a driving simulator with subjects residing in Oregon which has a long history of FYA use. There is a need for additional research to give clear guidance on the appropriate vehicle and pedestrian volume thresholds and questions remain about the display of the FYA during the pedestrian walk and clearance interval.

Acknowledgments

The research was sponsored by the Oregon Department of Transportation (SPR 789).

Author Contributions

The authors confirm contribution to the paper as follows—study conception and design: DSH and CM; data collection: HJ and SK; analysis and interpretation of results: HJ, SK, DSH, and CM; draft manuscript preparation: HJ, CM, DSH and SK. All authors reviewed the results and approved the final version of the manuscript.

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The Standing Committee on Traffic Control Devices (AHB50) peer-reviewed this paper (19-06076).