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Do drivers correctly interpret the solid circular green from an exclusive right-turn bay?

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Abstract

In 2016, the U.S. recorded the highest number of pedestrian fatalities since 1990. Turning vehicles pose a collision risk for non-motorized road users. To improve traffic safety and efficiency at signalized intersections, driver behavior associated with right-of-way transitions at signalized intersections must be understood more comprehensively. This study explored the safety concern of driver's potential to incorrectly interpret the solid circular green (SCG) during right-turns using a high-fidelity driving simulator. A counter-balanced, factorial design was chosen to explore two independent variables: signal indication type and presence of a pedestrian. The pre-turn speed, visual attention and driver decision making were used as performance measures. Data were obtained from 46 participants (21 women) turning right 184 times in 4 experimental scenarios. Two linear mixed effects models and a frequency analysis were used to examine within-subject variables on observed performance. Results from both the frequency analysis and the statistical model suggest that for the same turning maneuver, drivers presented a SCG were less likely to exhibit correct behavior. While drivers had similar speed for both the SCG and solid green arrow (SGA) signals, drivers fixated on the SGA head longer. The similar speed indicates that drivers are interpreting the SCG as a protected indication. When presented with the SCG indication in the presence of pedestrians, 33% of drivers exhibited improper behavior while turning right, resulting in a situation with high crash potential. For the same turning maneuver, drivers presented with SGA indication were more likely to exhibit correct behavior. This indicates that SGA can promote a safer interaction between right turning vehicles and pedestrians in the conflicting crosswalk. These findings provide quantitative data that could be used by transportation agencies to improve driver comprehension and pedestrian safety at signalized intersections.

Keywords – right-turns, safety, traffic operations, linear mixed effects model, solid circular green, solid green arrow

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1. Introduction

Pedestrian and bicyclist fatalities account for nearly one-third of all fatalities at signalized intersections in the United States [1]. Pedestrian fatalities at signalized intersections are often the result of vehicles failing to yield right of way while turning right or left [1]. Often this is due to the failure of drivers signalized intersections to complete the five psychological steps that allow them to see and comprehend an object such as a pedestrian (selection, detection, recognition, location, and prediction) [2].

Traditional signalized intersection phasing places pedestrian movements in direct conflict with the movements of turning vehicles. Additionally, turning movements through signalized intersections often require drivers to yield right of way to oncoming traffic, pedestrians, and bicyclists. This requirement for drivers to yield while turning often place conflicting pedestrians at higher risk [1].

Right turns at a signalized intersections can be categorized as either: (1) right turns that have the right of way (ROW), or (2) right turns that must yield, to be consistent with the rules of the road [3]. A protected right turn, indicated by the SGA, falls into the first category of right-turn movements: the ROW is provided, and no conflicting vehicles (or pedestrians) are allowed [3]. A permissive right turn, typically indicated by the SCG, falls into the second category: drivers are only allowed to proceed through the intersection if there is an acceptable gap in the conflicting flow of vehicles, including bicycles, or pedestrians [3].

This study explored the safety concern of driver's potential to incorrectly interpret the SCG during right-turns using a high-fidelity driving simulator. The goal of this work was to provide quantitative data that could be used by transportation agencies to potentially improve driver comprehension and pedestrian safety at signalized intersections.

1.1. Geometry

A protected right turn requires a dedicated right-turn lane (see Figure 1) that is used only by vehicles making right turns [3]. Through-traffic and right-turning traffic have differential 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 [4]. To mitigate this problem, the use of an exclusive right-turn lane may be appropriate [5]. Exclusive right-turn lanes improve safety and have the potential to improve the overall operation and efficiency of the intersection [5].

1.2. Pedestrian

Pedestrians are frequently assigned to a through-traffic movement, with the assumption that a vehicle must yield before making a right turn [6]. Conflicts between right-turn vehicles and pedestrians are more likely to occur when the SCG indication is displayed [7]. Road safety has generally increased significantly over the past years. However, the benefits of this increasing trend have not been evenly distributed. In fact, from 2007 to 2016, total motor vehicle fatalities decreased, while the number of pedestrian's fatalities increased. In the United States, for instance, crash reports state that approximately 5,987 pedestrians were killed in 2016, which is the highest since 1990 [8]. This indicates the necessity of finding solutions to enhance pedestrian safety.

Pedestrian space and delay are used to measure the pedestrian's level of service at signalized intersections. Hubbard et al. (2009) questioned whether this measure effectively reflects the negative effects that right-turning vehicles have on pedestrians. Factors affecting pedestrian safety were the pedestrian direction of travel, right-turn volume, volume of pedestrians crossing, whether the pedestrian arrived late, whether the pedestrian began crossing after the walk interval ended, and crosswalk characteristics [9].

1.3. Phasing

Protected right-turn movements are operated by the SGA, which allows drivers to proceed without providing any conflicts with other road users. Alternatively, permitted right-turn movements can be signalized with SCG. This indication allows vehicles and adjacent pedestrians to proceed at the same time.

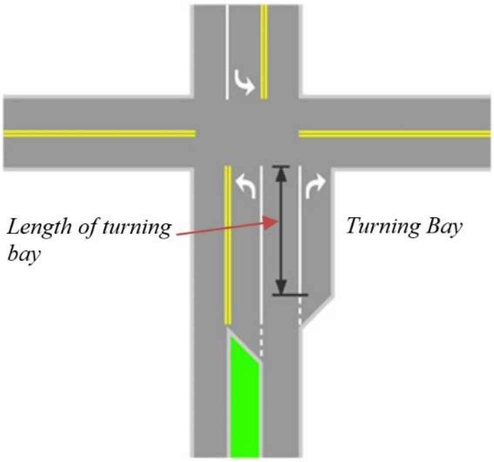

Fig. 1 - Example of exclusive right-turn design [1]

The Federal Highway Administration's (FHWA) Manual on Uniform Traffic Control Devices (MUTCD) provides a national standard for the application of traffic control devices [6]. Section 4D.05 C of the MUTCD indicates that a SCG signal should only be used to allow traffic to proceed in any lawful and practical direction. The MUTCD requires that under the SCG, vehicles must yield the right-of-way to pedestrians in crosswalks or other vehicles. While this distinction is clear in the MUTCD, crash data suggests that in some instances driver's proceed to make right turns during the circular green and fail to yield to pedestrians. This scenario is more common when drivers are involving in secondary tasks while driving [10, 11]. Moreover, the MUTCD defines the appropriate driver response to the SGA as identical to that of the circular green: proceed after yielding to conflicting vehicles and pedestrians. However, it also forbids use of the arrow with any conflicting movement; so, in practice, motor vehicles are always provided an exclusive movement with this display.

Improving the rate at which drivers detect pedestrians, especially during right turns, is vital for multimodal intersection safety. Generally, safety enhancements should reduce the number of conflict points between vehicles and pedestrians and make the conflict points more visible.

2. Methodology

An experiment was designed to examine driver behavior while executing right-turns using the performance measures of visual attention, speed, and comprehension score. Oregon State University's (OSU) Driving Simulator was used to observe these driver behaviors in a simulated driving environment.

2.1. 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 2). 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 [12].

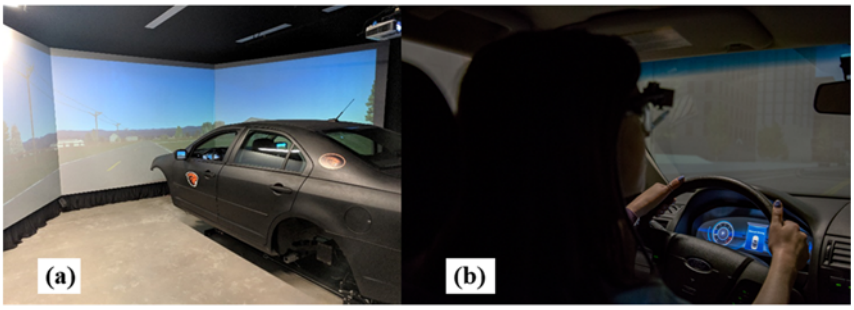

Fig. 2 - Views from (a) outside OSU driving simulator; (b) inside the OSU driving simulator

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 3.35 m by 2.29 m. A digital light-processing projector is used to display a rear image for the driver's center mirror. The two side mirrors have embedded LCD displays. 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.

2.2. Research objective

The study was designed to answer three primary research questions. 1) Is the visual attention of a right-turning motorist influenced by active indication or the crossing pedestrians? 2) How does the presence of a pedestrian relate to the speed of the vehicle during the right turning maneuver? 3) How is the driver's decision to stop, yield, or go in influenced by right turn signal display and phasing?

2.3. Experimental design

A factorial design was chosen for this experiment to enable exploration of the interactions between the independent variables. Two independent variables were included in the experiment: 1) right-turn signal indication which has 2 levels (SCG and SGA), and 2) two levels of pedestrian presence in the conflicting crosswalk (one pedestrian crossing and no pedestrian).

The factorial design for the three independent variables resulted in the inclusion of 2×2 scenarios, which were presented within subjects. To control for practice effects [13], the order of right-turn scenarios presentation was counterbalanced and the placement of each scenario on each grid was randomly assigned. Thus, different track layouts were developed and presented in random order to each participant. Each track had four right-turning maneuvers (see Figure 3), and each right turn was randomly assigned one level for each of the two independent variables, and start and finish locations of these grids were varied.

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

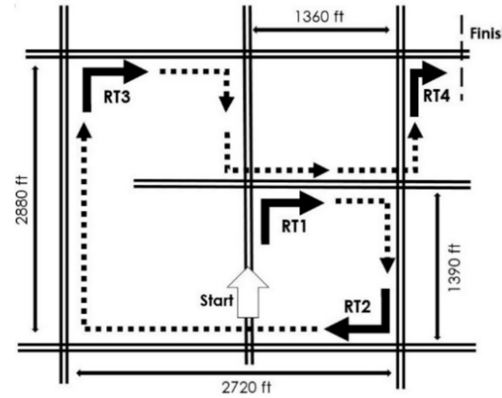

Fig. 3 - Grid layout with four right-turn scenarios

Intersection approaches included one through lane and an exclusive right-turn lane, 15.24 m in length, along with a single receiving lane for the right-turn movement. The posted speed limit was 56 km/h, surrounding land use was light-to-medium-density commercial and industrial development, and light ambient traffic was included. The roadway cross-section consisted of two 3.66 m traffic lanes in each direction with no median, while the cross-section of the roadway receiving the right-turn roadway consisted of two 3.05 m traffic lanes in each direction with no median. A yellow centerline, solid white edge line, small 0.30 m paved shoulder, and 1.98 m-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 4 provides an example of both signal heads as seen in the simulator from the perspective of an approaching driver.

Once the vehicle entered the exclusive right turning bay, there was a proximity sensor that triggered the pedestrian in the simulation to start walking from the near side. 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. In the SGA scenario, one pedestrian was located at the corner of the nearside sidewalk waiting for the WALK pedestrian signal indication. The scenario was designed so that the driver could clearly see the pedestrian.

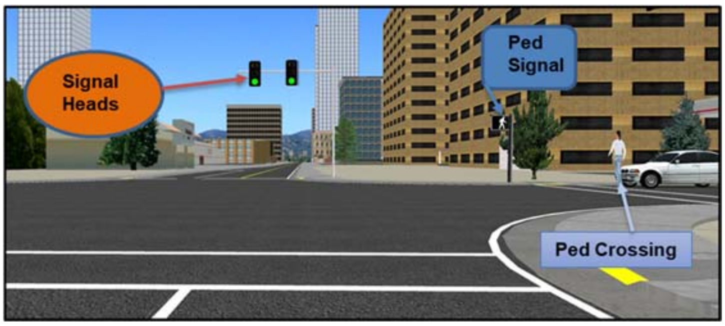

Fig. 4 - Example of signal and pedestrian head configurations in the simulator environment

2.4. Participant demographics

A total of 52 individuals (25 women), primarily from the community surrounding Corvallis, Oregon, were participants in the experiment. Participants 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 30.9 years (SD= 11.9) among those 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).

2.5. Data collection

After the motorist's eyes were calibrated to the driving simulator screens, participants completed a five-minute 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, participants were instructed to begin the experiment. Participants were instructed to turn right, left, or drive through the intersection by an automated voice command set to announce twice at 121.92 m and 60.96 m in advance of the intersection. Figure 3 shows an example grid layout with four right-turning scenarios (there were six tracks to drive).

Three primary dependent variables were extracted from the experimental data. First, driver decision making was observed from video recordings and measurements of speed and coded as (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 indication or other areas of interest. Finally, instantaneous speed of participant vehicle in the turning bay was measured by the simulator. Driver behavior and vehicle response data were collected by the SimObserver data acquisition platform during the experiment. A complete data file was generated for each participant for each of the 4 experimental drives. A total of 20 hours of video and vehicle characteristics (e.g., speed) 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 milliseconds.

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 (4 per participant). These video segments were cropped to the length of time that the driver entered the turning bay (generally 10–30 seconds). Researchers drew AOI polygons on individual video frames in a sequence separated by intervals of approximately 5–10 frames. The ETAnalysis software was used to calculate the fixation data on each AOI. Motorist's eye-tracking data were analyzed from the point when the participant entered the turning bay at the intersection and continued until the participant completed the right-turn maneuver.

2.6. Linear Mixed Effect Model

A Linear Mixed Effect Model (LMEM) was chosen for this analysis because 1) it can handle the errors generated from repeated subject variables as the participants are exposed to all scenarios, 2) it can handle fixed or random effects, 3) categorical and continuous variables can easily be accommodated, and 4) the probability of Type I error occurring is low [14]. A potential limitation of LMEM is that more distributional assumptions need to be addressed [15]. The sample size for this study was 46 participants, which is greater than the minimum of 20 required for a LMEM analysis [16]. The LMEM is formulated as shown in equation (1),

$$y_{ij} = \beta_0 + \beta_1 x_{ij} + b_i + \varepsilon_{ij}\ , b_i \sim \mathrm{N}\,(0,\sigma_b^2),\ \ \varepsilon_{ij} \sim \mathrm{N}\,(0,\sigma_\varepsilon^2) \tag{1}$$

where β_0 is the intercept at the population level, β_1 is the slope. b_i is the random intercept of the i^{th} participant that is following a mean normal distribution with variance σ_b^2, and ε_{ij} is the error. Hence, b_i and ε_{ij} are assumed to be independent.

The model was developed using the statistical software Minitab for Windows (version 18.1) to consider the independent variables of signal indication and presence of pedestrian. These variables were included in the model as fixed effects. Random effects for the participant variable were also included in the model.

A LMEM was used to estimate the relationship between independent factors and participant's mean speed, and total fixation duration TFD, which is appropriate given the repeated measures nature of the experimental design, where each participant experienced each scenario [15]. It was necessary that both fixed and random effects be included in the model.

Pearson's correlation coefficient was used to identify any correlated variables. In the case of statistically significant effects, custom post hoc contrasts were performed for multiple comparisons using Fisher's Least Significant Difference (LSD). All statistical analyses were performed at a 95% confidence level. Restricted Maximum Likelihood estimates were used in development of this model.

3. Results and analysis

3.1. Speed

For each right-turning maneuver, the average speed (km/h) of the participants' vehicle for the length of the 15.24 m turning bay until the stop line was recorded. Table 1 shows the mean (μ) and standard deviation (SD) values for speed for each level of every independent variable. As shown in the table, the highest mean speed occurred with the SCG indication when a pedestrian was not present (μ= 35.97, SD=5.37 km/h). The lowest mean speed occurred with the SGA indication when a pedestrian was present (μ= 33.86, SD=5.57 km/h).

Tab. 1 - Descriptive statistics of average speed in the turning bay (km/h)

Signal Indication	**Descriptive Statistics**	**Presence of Pedestrian**	
		With Pedestrian	**Without Pedestrian**
Steady Green Arrow (SGA)	μ (SD)	33.86 (5.57)	34.30 (6.50)
Steady Circular Green (SCG)	μ (SD)	34.26 (6.39)	35.97 (5.37)

Tab. 2 - Summary of estimated models of average speed in the turning bay

Model	Variables	Levels	Estimate	DF	p-value
SCG and SGA	Subject random effect (SD)	**-**	**5.02**	**-**	**<0.001**
	Constant	**-**	**34.58**	**45**	**<0.001**
	Signal Indication	**SCG**	**1.06**	**135**	**0.051**
		SGA	*Base Value*	-	-
	Presence of Pedestrian	**PED**	**-1.07**	**135**	**0.042**
		NO PED	*Base Value*	-	-
	Signal x Pedestrian	**SCG X PED**	**-0.60**	**135**	**0.202**
		SCG X NO PED	*Base Value*	-	-
Summary Statistics					
R^2	77%	Observations			184
-2Log Likelihood	902.02	Subjects			46
		Observation/subject			4

***Bold**: Estimated variable*

A LMEM was used to statistically examine differences in mean speed. The results of the model are shown in Table 2. The LMEM for SCG and SGA found that the signal indication treatment is not statistically significant (p = 0.05), but the presence of pedestrian is (p = 0.04). This suggests that regardless of the presence of the pedestrian, drivers tend to interpret the SCG as a "go" indication. The interaction term between the two treatments is also not statistically significant. The random effect was significant (Wald Z=4.25, p<0.001). This supports the argument that a LMEM has higher efficiency compared with a fixed effect linear regression model. Regardless of signal type, there is a suggestive probability that participants have higher speed (about 1 km/h) without the presence of pedestrians (p=0.04)

The two-way treatment interaction was not statistically significant. However, they were considered in the pairwise comparison for signal indication and presence of a pedestrian. Figure 5 plots the mean speed at each level of signal indication, and presence of a pedestrian. The only statistically significant pairs were the SCG display in the absence of pedestrians and the SGA display in the presence of pedestrians (p < 0.001). In terms of practice, the difference in speed between the two scenarios (2.11 km/h) may not be functionally important, though it is statistically significant. Visual inspection of the mean speed in Figure 5 reveals that drivers did not differentiate between the SCG and SGA display. In other words, they interpreted the green indication as communicating "go".

3.2. Visual attention

While the driver traversed the length of the right turning bay, the number and duration, in seconds, of participants' fixations on AOI (the overhead signal) were recorded, with a total fixation duration (TFD) of 0 seconds (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 3 shows the mean (μ) and standard deviation (SD) values for TFD for each level of every independent variable. As shown in the table, the highest mean TFD (1.09 secs) occurred with the SGA indication when a pedestrian was not present. The lowest mean TFD (0.47 secs) occurred with the SCG indication without a pedestrian.

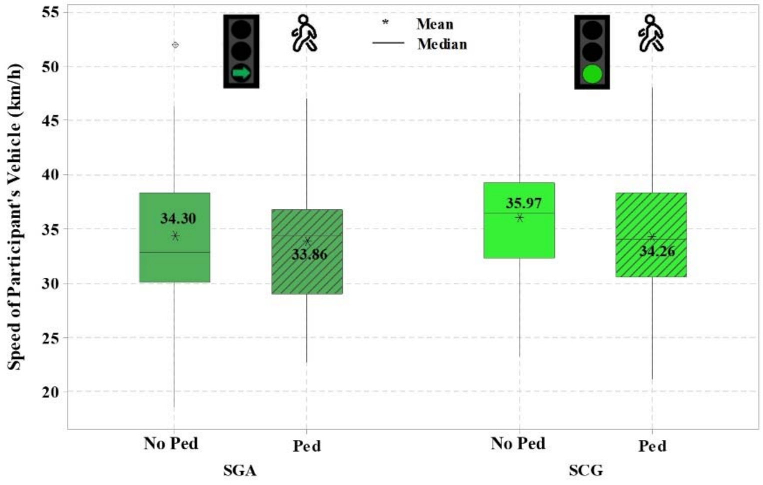

Fig. 5 - Two-way interactions on mean speed for SCG and SGA indications

Tab. 3 - Descriptive statistics of average total fixation duration (secs)

Signal Indication	**Descriptive Statistics**	**Presence of Pedestrian**	
		With Pedestrian	**Without Pedestrian**
Steady Green Arrow (SGA)	μ (SD)	1.07 (0.73)	1.09 (0.82)
Steady Circular Green (SCG)	μ (SD)	0.55 (0.66)	0.47 (0.42)

Tab. 4 - Summary of estimated models of average TFD

Model	**Variables**	**Levels**	**Estimate**	**DF**	**p-value**
SCG and SGA	Subject random effect (SD)	-	**0.35**	-	**0.003**
	Constant	-	**1.59**	**42**	**<0.001**
	Signal Indication	**SCG**	**-0.58**	**126**	**<0.001**
		SGA	*Base Value*	-	-
	Presence of Pedestrian	**PED**	**0.02**	**126**	**0.778**
		NO PED	*Base Value*	-	-
	Signal x Pedestrian	**SCG X PED**	**0.08**	**126**	**0.603**
		SCG X NO PED	*Base Value*	-	-
Summary Statistics					
R^2	49%	Observations			172
-2Log Likelihood	350.31	Subjects			43
		Observation/subject			4

***Bold**: Estimated Variable*

A modeling approach similar to the one that was followed for the speed was used to statistically examine differences in mean TFD. The results of the model are shown in Table 4. The LMEM for SCG and SGA found that the presence of a pedestrian is not statistically significant (p = 0.79), but the signal indication is (p <0.001).

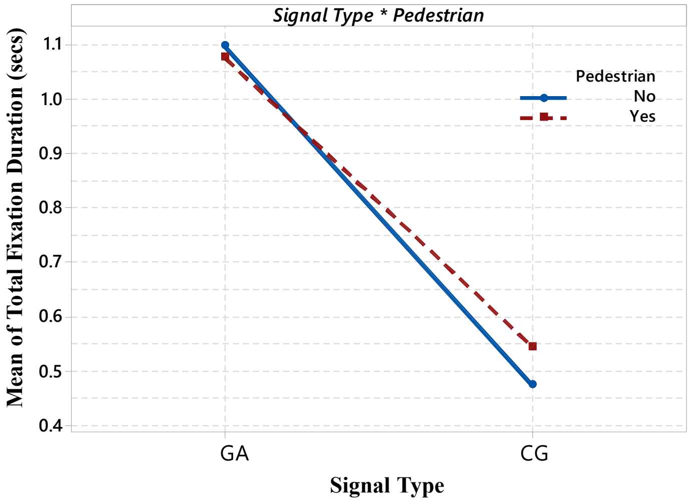

Fig. 6 - Two-way interactions on mean TFD for SCG and SGA indications

This suggests that regardless of the presence of pedestrians, drivers fixate longer on the traffic signal display when encountering the SGA compared to SCG. The interaction term between the two treatments is also not statistically significant. The random effect was significant (Wald Z=2.70, p=0.003). On average, participants encountering a SGA indications are spending a longer time (about 0.5 seconds) observing the display (p <0.001) while turning right.

The two-way treatment interaction was not statistically significant. However, they were considered in the pairwise comparison for signal indication, and presence of a pedestrian. Figure 6 plots the mean TFD at each level of signal indication, and presence of a pedestrian. The only statistically significant pairs were when participants encountering SGA have a higher fixation time with or without the presence of pedestrians (p < 0.001).

3.3. Driver comprehension

The captured video of each right-turning maneuver in the simulator was carefully reviewed and classified into three categories: each correct response was given a comprehension score of 2, partially correct response was coded as 1, and an incorrect response was coded as 0, based on established criteria shown in Table 6. The frequency distribution for the three comprehension scores at each level of each independent variable is shown in Table 5. Participants turning right on the SGA indication had the highest correct comprehension score based on the observed behavior in the simulator. The correct comprehension scores are higher in the absence of a pedestrian, which reported the highest frequency count (45 out of 46). The SCG display had comparable comprehension scores in the presence of a pedestrian (31), 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 SCG indication. This suggests that an alternative display should be considered to improve driver response to the permissive nature of the movement (i.e., they recognize the need to check for conflicts). The incorrect/partially incorrect comprehension score for the SGA indication is possibly a carry-over effect since drivers were presented with SCG displays in the same track.

Tab. 5 - Frequency of comprehension score

Signal Indication	**Descriptive Statistics**	**Presence of Pedestrian**	
		With Pedestrian	**Without Pedestrian**
Steady Green Arrow (SGA)	Choices Frequency (46)	(0, 1, 2) (1, 6, 39)	(0, 1, 2) (0, 1, 45)
Steady Circular Green (SCG)	Choices Frequency (46)	(0, 1, 2) (11, 4, 31)	(0, 1, 2) (3, 9, 34)

The same error coding paradigm followed by Hurwitz et al., 2018 was used (see Table 6) [17]. For the SCG, to be coded as correct, participants must turn right after yielding to pedestrians (if present) in the crosswalk. Partially correct actions resulted from 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 drivers coming to a complete stop (vehicle speed < 1.61 km/h) to check for pedestrians, or a crash with a pedestrian. Driver responses were coded as correct if they turned right without stopping, recognizing that the steady green arrow (SGA) indicates a protected right-turn movement. A response was coded partially incorrect if drivers slowed down or checked for pedestrians and other conflicting movements before turning. The incorrect action resulted from drivers coming to a complete stop (vehicle speed < 1.61 km/h) while checking for pedestrians. The circular green indication was evaluated in the simulator in scenarios with or without a pedestrian present. Proportions of correct actions ranged from 67% (with pedestrian) to 74% (without pedestrian), partially correct actions ranged from 7% (without pedestrian) to 9% (with pedestrian), and incorrect actions ranged from 7% (without pedestrian) to 24% (with pedestrian). These incorrect responses caused 11 crashes or near-miss crashes during 46 right turns in the presence of pedestrians. This finding suggests the potential negative impact of drivers considering that the SCG is similar to SGA, and therefore, their speed was similar when they were driving in the turning bay.

Tab. 6 - Error coding of narrative for the simulator experiments

Display Indication	**Correct**	**Partially Correct**	**Incorrect**
Circular Green (SCG)	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 < 1.61 km/h) to check for pedestrians (or) A crash with pedestrian
Steady Green Arrow (SGA)	Turn right without stopping, recognizing that the SGA indicates a protected right-turn movement	Check for pedestrians and turn right (or) slow down and check for pedestrians and other cross traffic but did not recognize the protected movement in either case	Stop before turning (vehicle speed < 1.61 km/h) to check for pedestrians

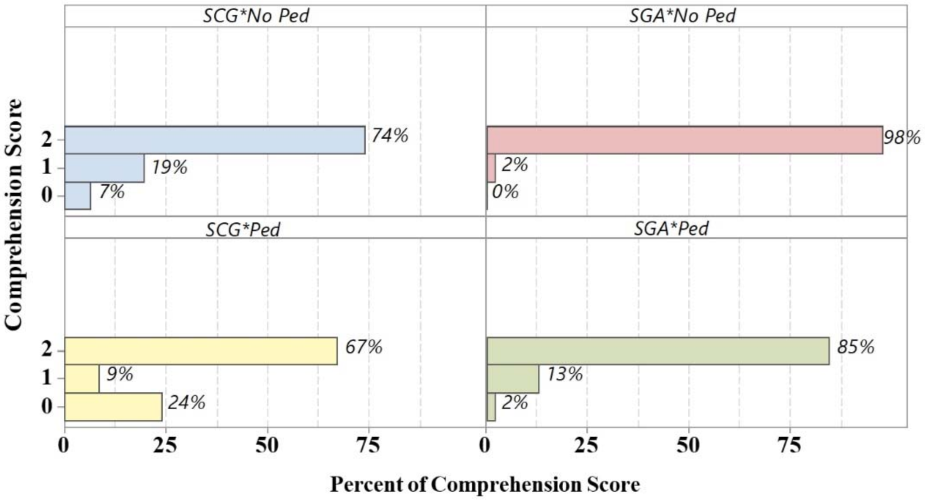

Fig. 7 - Percent of comprehension score for SCG and SGA indications by the presence of pedestrians

High proportions (85%-98%) of correct actions were observed among simulator participants responding to the SGA indication with and without a pedestrian. Responses deemed as partially correct varied between 2% and 13%. Low levels of incorrect responses were observed (0%-2%). These results indicate that the SGA indication was well understood by driving simulator participants. As mentioned, the MUTCD defines the appropriate driver response to the SGA as identical to that of the circular green (proceed after yielding to conflicting vehicles and pedestrians) but forbids use of the arrow with any conflicting movement. This may explain the 2%-13% of partially incorrect behavior.

4. Conclusions

This paper examined driver comprehension and behaviors with respect to two right-turn movements, protected and permitted with a focus on the SGA versus SCG in a driving simulator. A counter-balanced factorial design experiment was conducted in the simulator to explore driver comprehension, speed, and visual attention using two independent variables - signal indication type, and presence of pedestrians. Using data from 46 participants, two LMEM were used to study the impacts of treatments on the visual attention and speed of participants. In summary, the results of this simulator experiment suggest that the SGA indication provides safer environment for the pedestrians by decreasing less desirable vehicle-pedestrian interactions. Both in the descriptive data and in the models, for the same turning maneuver, drivers presented a SCG were less likely to exhibit correct behavior. While drivers had similar speed for both the SCG and SGA signals, drivers fixated on the SGA head longer. The similar speed suggests that drivers may be interpreting the SCG as a protected indication. Similar results were observed in a left-turn movement experiment [18]. Therefore, SGA can promote a safer intersection. However, the negative impact of using this scheme causes delay at the intersection for all users since pedestrian phasing would not be able to run concurrently with the vehicle turn. Longer delays might encourage pedestrians and drivers to disregard the signal indications. In concert with prohibiting right-turn on red, completely separating turning vehicles from pedestrians could have significant safety benefits, especially in areas of pedestrian activity. Another possible option is to use flashing yellow arrow display on right turns in lieu of a steady circular green display to better communicate to drivers the permissive nature of the right-turn [17, 19].

4.1. Limitations and future work

Although the within-subject design of the driving simulator provides the potential for increased statistical power, a potential limitation is fatigue effects, which can cause a participant's performance to degrade over the course of the experiment as they become tired or bored. The order of the scenarios was partially randomized, drive times were minimized, and breaks were introduced between drives to limit the influence of fatigue effects.

Acknowledgments

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References

1. FHWA. (2018). "Intersection Safety - Signalized Intersections." Mitigation Strategies For Design Exceptions – Safety.
2. Warner, Jennifer, et al. "A Simulator-Based Analysis of Engineering Treatments for Right-Hook Bicycle Crashes at Signalized Intersections." Accident Analysis & Prevention, vol. 104, 2017, pp. 46–57., doi:10.1016/j.aap.2017.04.021.
3. USDOT. (2015). National Cooperative Highway Research Program: Signal Timing Manual Second Edition.
4. FHWA. (2004). Signalized Intersections: Informational Guide. US Department of Transportation.
5. ODOT. (2012). "Chapter 8 Intersections." Highway Design Manual. ODOT. (2015). Traffic Signal Policy and Guidelines.
6. FHWA. (2008). Traffic Signal Timing Manual.
7. Kumar, A., Paul, M., & Ghosh, I. (2019). Analysis of Pedestrian Conflict with Right-Turning Vehicles at Signalized Intersections in India. Journal of Transportation Engineering, Part A: Systems, 145(6), 04019018.
8. National Center for Statistics and Analysis. (2018, March–Revised). Pedestrians: 2016 data. (Traffic Safety Facts. Report No. DOT HS 812 493). Washington, DC: National Highway Traffic Safety Administration.
9. Hubbard, S. M., Bullock, D. M., & Mannering, F. L. (2009). Right turns on green and pedestrian level of service: Statistical assessment. Journal of Transportation Engineering, 135(4), 153-159.
10. Jashami, H., Abadi, M.G., Hurwitz, D.S., 2017. *Factors Contributing to Self-Reported Cell Phone Usage by Younger Drivers in the Pacific Northwest.* In: The 9th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design. Manchester Village, VT.
11. Jashami, H., Hurwitz, D. S., Abdel-Rahim, A., Bham, G. H., & Boyle, L. N. (2017). Educating Young Drivers in the Pacific Northwest on Driver Distraction. Transportation Research Board 96th Annual Meeting, Washington DC, United States. (No. 17-02233).
12. Swake, J., M. Jannat, M. Islam, and D. Hurwitz. Driver Response to Phase Termination at Signalized Intersections: Are Driving Simulator Results Valid? Presented at the 7th International Driving Symposium on Human Factors in Driving Assessment, Training, and Vehicle Design, Bolton Landing, NY, 2013.
13. Cobb, G. W. Introduction to Design and Analysis of Experiments. Springer, New York, 1998.
14. Jashami, H., Hurwitz, D. S., Monsere, C., & Kothuri, S. (2019). Evaluation of Driver Comprehension and Visual Attention of the Flashing Yellow Arrow Display for Permissive Right Turns. *Transportation Research Record*, 0361198119843093.

15. Maruyama, N., 2008. Generalized Linear Models Using Trajectories Estimated from a Linear Mixed Model. Kitasato University.
16. Barlow, Z., Jashami, H., Sova, A., Hurwitz, D. S., & Olsen, M. J. (2019). Policy processes and recommendations for Unmanned Aerial System operations near roadways based on visual attention of drivers. *Transportation Research Part C: Emerging Technologies, 108, 207-222.*
17. Hurwitz, D., Jashami, H., Buker, K., Monsere, C., Kothuri, S., & Kading, A. (2018). *Improved Safety and Efficiency of Protected/Permitted Right-Turns in Oregon* (No. FHWA-OR-RD-18-14).
18. Knodler Jr, M. A., Noyce, D. A., Kacir, K. C., & Brehmer, C. L. (2006). Potential application of flashing yellow arrow permissive indication in separated left-turn lanes. Transportation research record, 1973(1), 10-17.
19. Kothuri, S., Monsere, C., Jashami, H., & Hurwitz, D. S. (2020). Online Survey of Driver Comprehension of the Flashing Yellow Arrow for Right-Turn Signal Indications. *Journal of Transportation Engineering, Part A: Systems*, 146(7), 04020058.