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A Simulator-Based Analysis of Engineering Treatments for Right-Hook Bicycle Crashes at Signalized Intersections

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ABSTRACT

A right-hook crash is a crash between a right-turning motor vehicle and an adjacent through-moving bicycle. At signalized intersections, these crashes can occur during any portion of the green interval when conflicting bicycles and vehicles are moving concurrently. The objective of this research was to evaluate the effectiveness of four types of engineering countermeasures – regulatory signage, intersection pavement marking, smaller curb radius, and protected intersection design – at modifying driver behaviors that are known contributing factors in these crashes. This research focused on right-hook crashes that occur during the latter stage of the circular green indication at signalized intersections with a shared right-turn and through lane. Changes in driver performance in response to treatments were measured in a high-fidelity driving simulator. Twenty-eight participants each completed 22 right-turn maneuvers. A partially counterbalanced experimental design exposed drivers to critical scenarios, which had been determined in a previous experiment. For each turn, driver performance measures, including visual attention, crash avoidance, and potential crash severity, were collected. A total of 75 incidents (47 near-collisions and 28 collisions) were observed during the 616 right turns. All treatments had some positive effect on measured driver performance with respect to the right-turn vehicle conflicts. Further work is required to map the magnitude of these changes in driver performance to crash-based outcomes.

1. Introduction

Cycling is viewed as an integral component of the multimodal transportation system in the long-range plans of many cities in the United States. As cities have invested in nonmotorized transportation infrastructure to realize this goal, bicycling has become a meaningful alternative mode of transportation for commuting to activities such as school, work, shopping, and recreation (Pucher et al., 1999, 2006, 2011). However, even with these investments, safety remains an important issue. In 2011 alone, there were 677 bicyclist fatalities and 48,000 bicyclist injuries in the United States (NHTSA, 2013). One of the more prevalent bicycle-motor vehicle crash types at intersections is the *right-hook crash*, a collision that occurs between a right-turning vehicle and an adjacent through-moving cyclist. Between 2007 and 2011, right-hook crashes represented over 500 of reported crashes involving cyclists and 59% of all bicycle-motor vehicle crashes at signalized intersections in Oregon (Hurwitz et al., 2015). Many more crashes or near misses are not reported. Therefore, this type of crash is a safety concern for bicyclists.

There are some published insights into the causal factors behind these crashes. The Institute of Transportation Engineers (ITE) reported that in nearly 70% of bicyclist-motor vehicle collisions at intersections, the motorist reported that “they did not see the bicyclist before the collision” (ITE, 2004). In an earlier phase of this research, Hurwitz et al. (2015) reported that failures in the situational awareness of the driver significantly contributed to the occurrence of right-hook crashes. Specifically, the driver failed to look for the bicyclist, looked but did not see the bicyclist, or looked and saw the bicyclist but failed to predict their behavior accurately. Treatments that improve conspicuity of the bicyclist within the intersection may help to reduce the frequency of right-hook crashes.

The objective of this research was to determine the effectiveness of four types of engineering countermeasures (regulatory signage, intersection pavement marking, smaller curb radius, and protected intersection design) at modifying driver behaviors (driver visual attention, crash avoidance, and potential crash severity) that are known to contribute to right-hook crashes. Participants completed a series of right-turn maneuvers in a high-fidelity, motion-based driving simulator. A partially counterbalanced experimental design exposed drivers to critical scenarios. For each turn, driver performance measures were collected and analyzed to determine the effects of treatments on the occurrence of right-turn vehicle conflicts.

We previously identified the highest situational risk factors for drivers and cyclists, including the most common intersection geometries for right-hook crashes occurring in the state of Oregon (Hurwitz et al., 2015). In this paper, we analyzed driving simulator experiments under these critical conditions. We evaluated driver behaviors in collisions that occur during the latter green phase at signalized intersections with a bicycle lane and a shared right-turn and through lane. The term "latter green phase" refers to the second portion of the green signal phase, after the initial vehicle queue has cleared and the green signal indication is still displayed.

2. Literature review

There are many different types of engineering treatments related to bicycle safety, but very few have been identified or evaluated specifically for the right-hook crash scenario. This section reviews the known effects of pavement marking, signage, and geometric design features as they relate to bicycle-motor vehicle crashes.

2.1. Signage

The only right-hook crash signage approved by the U.S. *Manual on Uniform Traffic Control Devices* (MUTCD) is the R4-4 “Begin Right Turn Lane, Yield to Bikes” sign, which is meant to inform roadway users of the merging maneuver at signalized intersections with an exclusive right-turn lane and a bike lane (FHWA, 2009). The Oregon Department of Transportation (ODOT, 2013) suggests an additional option, the ODOT OR10-15b “Turning Vehicles Yield to Bikes” sign, applicable to the mitigation of right-hook crashes occurring at signalized intersections with a shared right-turn and through lane.

Right-hook crash signage is often used in conjunction with another right-hook crash treatment, such as colored pavement markings. The National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide* states that “A ‘Yield to Bikes’ sign should be used at intersections or driveway crossings (with colored pavement marking) to reinforce that bicyclists have the right-of-way at colored bike lane areas”. This guide provides three alternative designs that are variations of existing MUTCD-approved signage (NACTO, 2011a). The City of Portland, OR (1999) found that the additional “Yield to Bikes” sign was a critical aspect of the effectiveness of blue pavement marking (intended to help roadway users identify the potential conflict area), as “substantially more motorists who noticed the sign correctly identified the meaning of the blue area”. The authors suggested that the supplementary sign is even more important than the blue pavement markings, due to its clarification of the regulatory message and the prioritized right-of-way. In another study by Brady et al. (2011), however, the signage did not appear to alleviate driver confusion over the appropriate yielding behavior. The researchers reported a reduction in driver yielding after installation of a similar sign. They concluded that driver confusion would likely occur over whether to cross the green-colored bicycle lane or to cross after the colored section.

2.2. Pavement markings

Most guidance and research on pavement marking designs in the context of right-hook crashes relate to treatments for signalized intersections with exclusive right-turn lanes, such as intersection crossing markings (e.g., dotted bike lane extensions, elephants' feet markings, bicycle symbols, sharrow symbols, or colored pavement). Pavement markings may raise awareness of intersection conflict areas for bicyclists and motorists and may positively influence driver yielding behaviors (NACTO, 2011a; Sundstrom and Nabors, 2014; Department for Transport, 2008; PBIC, 2002). Furthermore, U.S. guidance documents reinforce the optional use of dotted bicycle lane lines with or without colored pavement to designate a bicycle lane across an intersection (NACTO, 2011a; FHWA, 2009; FHWA, 2011; ODOT, 2011).

Although design guidance exists, there is little experimental research on the effectiveness of these treatments. Several before-and-after studies evaluated the effectiveness of colored pavement treatments for conflict areas. However, very few studies have focused specifically on impacts to driver behavior in an experimental manner. Most before-and-after studies generally found that colored pavement markings positively influenced driver yielding behavior or crash rates (City of Portland, 1999; Hunter et al., 2008; Singh et al., 2011). However, one study in Austin, TX found that motorists were less likely to yield with these markings (Brady et al., 2011). Researchers of that study hypothesized that the reduction in yielding was due to driver confusion over whether they should cross within or after the green-colored weaving area. They concluded that this confusion could be alleviated with an educational campaign. An experimental study at the University of Calgary evaluated four different bike lane crossing treatments at channelized right-turn conflict areas, using a full-cab driving simulator and an Applied Science

Laboratories (ASL) eye-tracking system (Caird et al., 2008). Although results for two of the four treatments were not presented, the authors showed that a blue skipped pavement marking treatment resulted in a higher yielding rate (90%) than a sharrow symbol treatment (77%).

2.3. Geometric design

Effects of geometric elements on right-hook bicycle crashes are not well documented. Reduction of the curb radius is a key element that has the potential to improve bicyclist safety at intersections by slowing down turning vehicles. This reduced velocity lessens the severity of collisions if they do occur and provides more time for the motorist or bicyclist to perform an avoidance maneuver. Multiple guidance sources recommend the use of smaller corner radii to improve pedestrian safety in a similar manner, but do not provide bicycle-specific curb radius design guidance (*ODOT, 2011; NACTO, 2013).*

Another, relatively novel, geometric design treatment for bicycle safety is the "protected" or Dutch-style intersection. Protected intersections incorporate a specific combination of geometric design and traffic engineering features to increase bicyclist safety and visibility. Literature regarding this design treatment largely comes from Europe, where these intersections are more common. For example, Goeverden and Godefrooij summarized before-and-after case studies of bicycle-related infrastructure interventions in the Netherlands. The common theme of these case studies was the redesign of intersections with respect to geometric design elements that are similar to those of protected intersections. Although these changes led to significant improvements in the perceived safety of the facilities, this effect "was not fully reflected by the observed decrease in accidents and casualties". However, because the Dutch bicycle infrastructure is already fairly well integrated into the Dutch transportation system, other countries may see “different (probably larger) impacts” (Goeverden and Godefrooij, 2011). At present, there is little U.S. guidance for protected intersections, although this situation is likely to change. The *Separated Bike Lane Planning & Design Guide*, recently released by the Massachusetts Department of Transportation (MassDOT, 2015), prominently features and describes protected intersections and associated best practices.

3. Methodology

To address the gaps in knowledge identified in the literature review and to mitigate the causal factors for right-hook crashes that were identified in a previous experiment (Hurwitz et al., 2015), we designed a second experiment to test various design treatments and controls in a simulated driving environment under specific environmental conditions. We examined and analyzed motorist behavior, including the right-turning motorists’ visual attention, crash avoidance behavior, and potential crash severity, in response to four different categories of possible right-hook crash treatments.

3.1. Driving simulator

The Oregon State University (OSU) Driving Simulator is a high-fidelity, motion-based simulator consisting of a full 2009 Ford Fusion cab mounted above an electric pitch motion system. This system is capable of rotating ±4° and allows for the commensurate representation of acceleration or deceleration. Three projectors display a front view of 180°. A fourth projector displays a rear image for the driver’s center mirror. Two side mirrors of the vehicle cab have embedded LCD displays. Simulator software records performance measures (e.g., velocity, position, and acceleration) at a sampling rate of 60 Hz. The virtual environment is created by using typical simulator software packages (Internet Scene Assembler and SimCreator) and design software (AutoCAD Civil 3D and Blender). Figure 1 shows views of the simulated environment from outside (a) and inside (b) of the vehicle.

a b c

Fig. 1 Views from (a) outside and (b) inside the OSU Driving Simulator. (c) Researcher wearing the eye-tracking device.

3.2. Eye tracker

Eye movement consists of fixations and saccades. Fixations occur when the gaze is directed towards a particular location and remains still for some period of time (Green, 2007; Fisher et al., 2011). Saccades occur when the eye moves from one point to another. The Mobile Eye-XG eye-tracker system (Fig. 1c) was used to collect information about the visual fixations and glance patterns of participants at a sampling rate of 30 Hz with an accuracy of 0.5°–1.0°. The participant's gaze was calculated from the correlation between the position of the pupil and the reflection of three infrared lights on the eyeball. The system recorded a fixation when the participant's eye paused in a certain position for more than 100 ms. For this research, only fixations were analyzed.

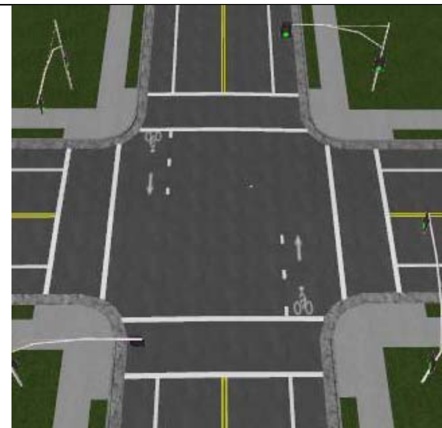
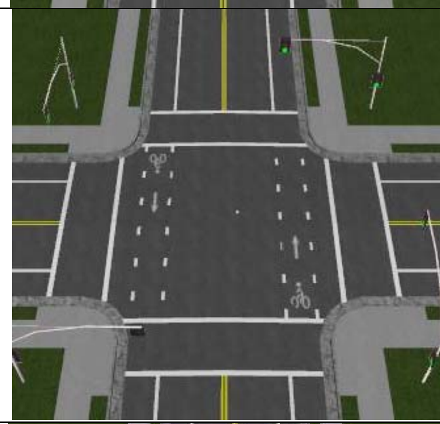
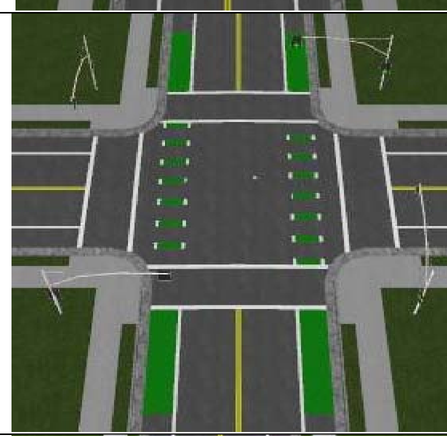
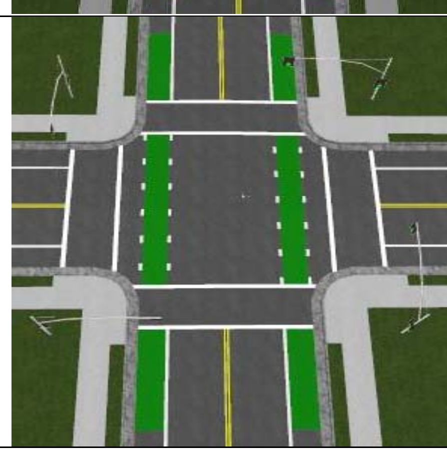
3.3. Treatment options

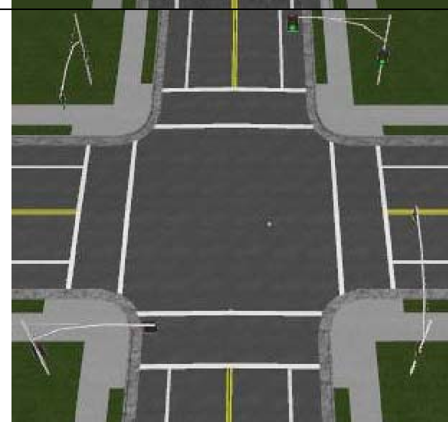
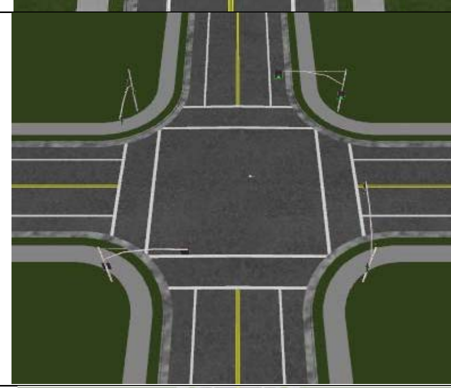
Four independent treatment variables were selected: signage, pavement marking, curb radius, and protected intersection design. Each independent variable was either dichotomous or categorical in nature and had two, three, or five levels (Table 1).

Table 1

Experimental Factors and Levels.

Variable	Level	Level Description	Image
Signage (S)	0	None	
	1	Signage	
Pavement Marking (PM)	0	None	

1	Dotted white bike line with stencil, single line	
2	Dotted white bike line with stencil, double line	
3	Skipped green bike lanes with white outline	
4	Full green bike lane with dotted white outline	

Curb Radius (C)	0	Larger curb radius, 30 ft.	
	1	Smaller curb radius, 10 ft.	
Protected Intersection Design (PI)	0	None	
	1	Protected intersection with islands	

2	Protected intersection with islands and green pavement markings	

3.4. Research hypotheses

The visual attention of motorists was measured by eye-movement fixation data, collected with a head-mounted mobile eye-tracker. The potential influence of experimental treatments on right-turning motorists' eye movement formed the basis of the research questions regarding the visual attention of motorists. The first research hypothesis was established to guide the assessment of visual attention for each individual treatment:

H_0: The engineering treatment has no effect on the right-turning motorist's mean total fixation duration on areas of interest (AOIs) in the driving environment.

Motorist performance was assessed with the global performance measure of crash avoidance during right-turning maneuvers in the latter portion of the green indication and in the presence of bicyclists at a signalized intersection. The consideration of crash avoidance behavior for intersection approaches with different treatments helped to determine the relative impact of the alternative treatments. The second research hypothesis was established to guide the assessment of crash avoidance behavior for each individual treatment:

H_0: The engineering treatment has no effect on the right-turning motorists' time-to-collision (TTC) values at the time of near-collisions or collisions.

Potential crash severity of incidents was measured by vehicle velocities, which were collected by the driving simulator. Higher velocities at the time of the traffic conflict were considered to be more severe, as injuries to the cyclist generally increase with higher velocities. By considering vehicle velocities for intersection approaches with different treatments, we were able to determine the relative impact of alternative treatments. The third hypothesis was established to guide the assessment of crash severity for each individual treatment:

H_0: The engineering treatment has no effect on the right-turning motorist's velocity at the time of near-collision or collision.

3.5. Experimental design

Environmental loading factors were selected by considering our previous findings regarding the causal factors of right-hook crashes at this type of signalized intersection configuration (2015). According to our results, the combined presence of oncoming turning vehicles and a bicyclist approaching from behind at a high speed (16 mph) was the worst-case casual scenario for right-hook crashes. In each of the experimental right-turn scenarios, the participant would experience the following environmental loading characteristics:

1. The signal would change to green before the driver approached the intersection, creating a "latter green phase";
2. An oncoming vehicle would turn left as the participant approached the intersection, and two more vehicles would be waiting in the oncoming lane with their turn signals illuminated;
3. Within fairly close proximity to the intersection, a bicyclist would appear in the driver's blind zone on the roadway, specifically located in the bicycle lane; and

4. The bicyclist would travel at a constant speed of 16 mph through the intersection, subsequently forcing the driver to yield the right of way, increase their speed to pass in front of the cyclist, or collide with the cyclist.

The cross-section of the roadway included two 12-ft. traffic lanes, with 6-ft. bicycle lanes in each direction. Intersection approaches included a single shared right-turn and through lane and a single receiving lane. Intersection approaches had posted speed limits of 35 mph. Fig. **1** shows an example of an intersection approach in the simulated environment as it was presented to the participant.

Fig. 1. Screen capture of an intersection approach in simulated environment.

To measure the influences of the treatment alternatives, participants were exposed to various treatment configurations. The experiment was a factorial design with 24 scenarios presented across six grids. Signage (two levels), pavement marking (five levels), and curb radius treatments (two levels) were fully counterbalanced against one another, resulting in 20 scenarios. Due to the design characteristics of this treatment, protected intersection treatment was only counterbalanced against signage treatment, resulting in four scenarios. Due to a coding error, two of the 24 scenarios were duplicated and the protected intersection treatment was not counterbalanced with the signage treatment. Therefore, the experiment included 22 unique scenarios across all treatments. This duplication was taken into consideration during the analysis of the resulting data.

Fig. **2** shows an example of the grid layout of four right-turning scenarios. The orange arrow "path" indicates the sequence of intersections that participants were asked to drive through. An automated voice command instructed participants to "Turn right at the next intersection". To control for practice or carryover effects, the order of the intersection grids was counterbalanced. In this randomized partial counterbalancing procedure, six different grid sequences were chosen and randomly presented to participants.

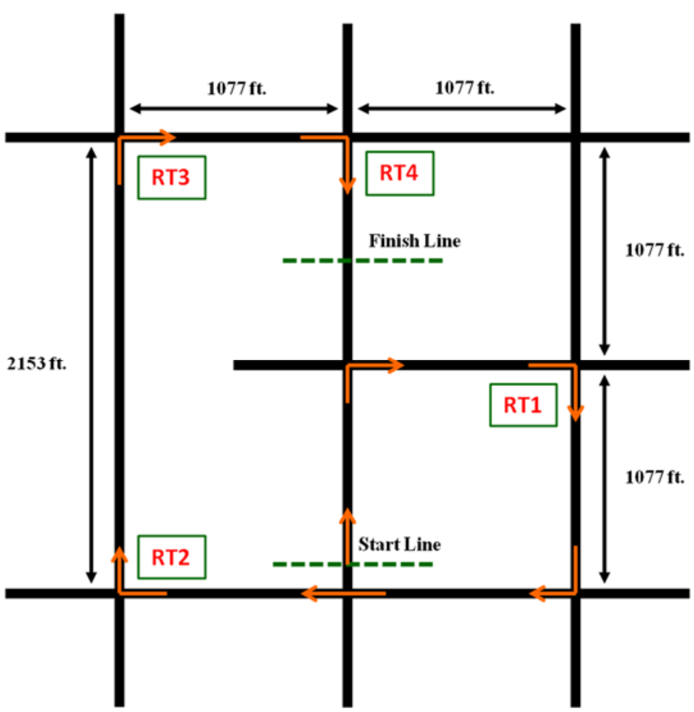


Fig. 2. Example of grid layout with four right-turning (RT) scenarios. Grid 5 Path: Start-Right-Right-Right-Thru-Right-Right-Right-Finish.

3.6. Participant demographics

Forty-six adults (26 men, 20 women) were recruited to participate in the driving simulator study. Seventeen participants (7 male, 10 female) experienced simulator sickness at various stages of the experiment, and their data were excluded from the final dataset. The final dataset comprised 28 participants (18 men, 10 women; mean age: 38 years, range: 18–70 years), who were recruited from among residents in the areas surrounding Corvallis, OR. They were required to be licensed (not necessarily Oregon-licensed) for more than 1 year, have good vision, and be able to provide written, informed consent. Due to limitations of the eye-tracking system equipment and calibration procedures, individuals wearing glasses were unable to participate unless they had contact lenses that provided them with adequate driving vision.

4. Results and discussion

All engineering treatments were evaluated with respect to visual attention, crash avoidance, and crash severity. For brevity, only the most significant finding in each measured area is discussed in detail.

4.1. Visual attention

Participants' eye-tracking data were analyzed to determine the effects of each engineering treatment on the amount of time that motorists spent scanning for the presence of bicyclists before completing the right-turn maneuver. Twenty-eight participants successfully completed the driving simulator experiment. However, due to eye-tracker calibration issues, 20 treatment intersections were lost across seven participants. As each treatment was only presented once to each participant, the remaining participants' data were still considered useable (a total of 596 right-turn maneuvers).

Table **2** summarizes the AOIs that were considered in the analysis of visual attention. Fig. **3** presents an annotated illustration of the AOIs. Although drivers were free to turn their heads, and although the simulator included rear-vision projection, true blind-spot checks were not possible. However, no subject in the simulator turned their head while making a turn.

Table 2

Summary of AOIs.

AOI	Description
Side Mirror with Bicyclist	Side mirror when bicyclist is present and visible within it
Rear Mirror with Bicyclist	Rear mirror when bicyclist is present and visible within it
Bicyclist	Bicyclist when in front of the vehicle or visible through the passenger side window
Side Mirror	Side mirror when no bicyclist is present or visible within it
Rear Mirror	Rear mirror when no bicyclist is present or visible within it
Turning Vehicle	Oncoming left-turning vehicles
Signal	Two traffic signal heads for direction of vehicle travel
Signage	Additional signage treatment
Pavement Marking	Additional pavement marking treatment
Protected Intersection Pavement Marking	Additional protected intersection pavement marking treatment
Protected Intersection Island	Additional protected intersection island treatment

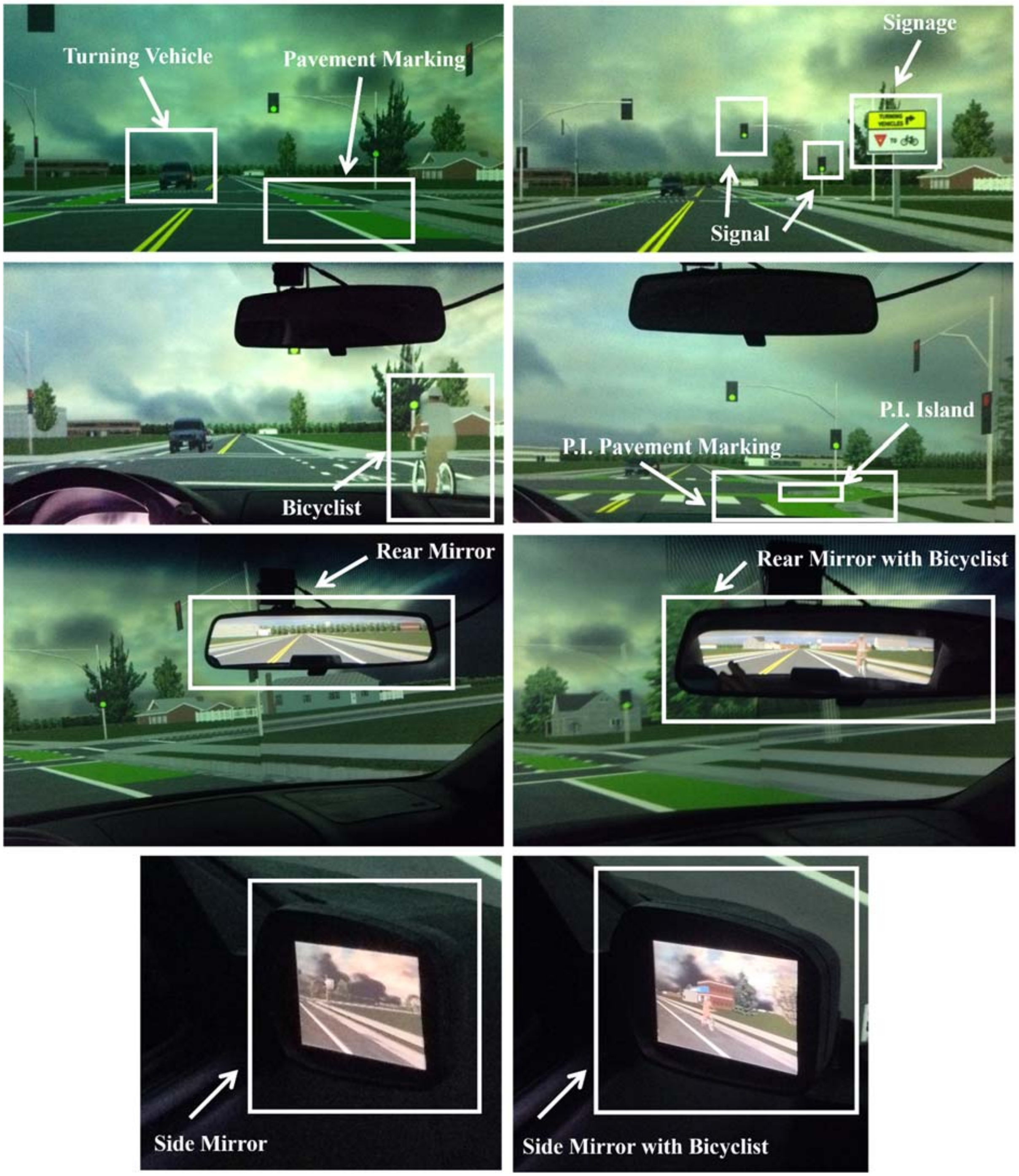


Fig. 3. Examples of the different AOIs considered during the experiment.

Average total fixation duration (ATFD) was calculated for each AOI and each treatment variable. ATFD provided a quantitative measure of how the motorist's visual attention was distributed across targets (Fisher et al., 2011). Table 3 presents the ATFD values for all AOIs, aggregated by treatment level.

Table 3

Summary of ATFD Values for All AOIs.

Treatment Type	Level	Bicyclist Side Mirror	Bicyclist Rear Mirror	Bicyclist	Side Mirror	Rear Mirror	Turning Vehicle	Signal	Pavement Marking	Prot. Int. Island	Signage
Signage	S0	0.63	0.50	0.35	0.48	0.63	2.16	0.98	1.21	0.62	
	S1	0.57	0.42	0.42	0.48	0.56	1.85	0.94	1.18	1.07	
Pavement Marking	PM0	0.64	0.48	0.31	0.55	0.58	2.01	1.15	1.07		
	PM1	0.75	0.42	0.31	0.41	0.68	2.23	0.93	1.31		
	PM2	0.62	0.42	0.35	0.51	0.50	1.93	0.94	1.10		
	PM3	0.60	0.40	0.44	0.46	0.68	1.92	0.72	1.34		
	PM4	0.45	0.53	0.39	0.47	0.58	1.92	1.01	1.17		
Curb Radius	C0	0.58	0.46	0.41	0.52	0.62	1.93	0.90	1.15		1.29
	C1	0.63	0.45	0.35	0.44	0.56	2.10	0.99	1.24		1.25
Protected Intersection	PI0 (T1)	0.62	0.43	0.28	0.62	0.71	1.97	1.24			
	PI0 (T11)	0.50	0.40	0.51	0.45	0.46	1.56	0.55			1.9
	PI1	0.49	0.69	0.59	0.62	0.69	2.44	1.06		1.62	
	PI2	0.57	0.57	0.36	0.71	0.34	2.01	1.01			1.07
	PI2	0.50	0.40	0.51	0.45	0.46	1.56	0.55		1.07	

Fixation data were statistically analyzed by a two-sample Welch's t-test for all AOIs by comparing ATFDs for the level-zero condition and each non-zero level condition. ANOVA was used to identify significant differences between ATFDs for the zero-level and non-zero levels. Results of these statistical analyses are presented in Table 4. ATFD distributions for the AOIs were strongly skewed to the right. Data were log-transformed, and zero values (i.e., data for participants who did not look at the AOI) were removed from the analysis. Thus, the statistical tests represent the subgroup of drivers who looked at the particular AOIs.

Table 4

Summary of Statistical Analyses of ATFD Values.

Treatment Type	Level	Bicyclist Side Mirror	Bicyclist Rear Mirror	Bicyclist	Side Mirror	Rear Mirror	Turning Vehicle	Signal	Pavement Marking	Prot. Int. Island	Signage
Signage	S1	0.46	0.07	0.31	0.88	0.66	0.001*	0.53	0.42	0.13	N/A
Pavement Marking	PM1	0.37	0.96	0.89	0.07	0.28	0.57	0.01*	N/A	N/A	0.49
	PM2	0.85	0.79	0.53	0.44	0.63	0.79	0.15	N/A	N/A	0.54
	PM3	0.43	0.56	0.23	0.28	0.09	0.47	0.001*	N/A	N/A	0.50
	PM4	0.03*	0.30	0.35	0.33	0.64	0.75	0.21	N/A	N/A	0.94
Curb Radii	C1	0.31	0.57	0.45	0.04*	0.93	0.21	0.38	0.50	N/A	0.76
Protected Intersection	PI1	0.68	0.15	0.02*	0.96	0.82	0.56	0.65	N/A	N/A	N/A
	PI2	0.48	0.67	0.38	0.19	0.27	0.17	0.13	N/A	N/A	0.19

* Statistically significant differences ($p \leq 0.05$).

Table 5 presents the distribution of participants who looked for the bicyclist in the side or rear mirror across all 596 right-turn maneuvers. Participants were considered to have looked for the bicyclist on the intersection approach if at least one of the bicyclist-related AOIs (Side Mirror, Rear Mirror, Bicyclist in Side Mirror, or Bicyclist in Rear Mirror) was greater than zero. Among the 596 right-turn maneuvers, 470 maneuvers (79%) involved participants looking for the bicyclist, and 126 maneuvers (21%) did not. Chi-square test results revealed no statistically significant difference between the frequencies of motorist fixations on the bicyclist at the different treatment levels.

Table 5

Summary of Motorist Fixations on Bicyclist.

Treatment Type	Level	Total (n)	Fixated	% Fixated	Chi-square
Signage	S0	296	228	77%	0.323
	S1	300	242	81%	
Pavement Marking	PM0	109	80	73%	0.168

	PM1	78	106	74%	
	PM2	90	109	83%	
	PM3	89	108	82%	
	PM4	91	110	83%	
Curb Radii	C0	325	260	80%	0.518
	C1	271	210	77%	
Protected Intersection	PI0 (T1)	26	20	77%	0.791
	PI0 (T11)	28	21	75%	
	PI1	27	20	74%	
	PI2	27	22	81%	

4.1.1. Discussion

For the crash potential metric, signage treatment had the greatest effect on behavior. Fig. 5. shows the ATFDs with 95% confidence intervals on the 11 AOIs for the signage treatment levels (S0, no signage present and S1, signage present). A generally positive pattern of change was observed between ATFDs for the two levels of signage treatment. ATFDs for the Side Mirror and Bicyclist in Side Mirror AOIs increased with S1 treatment. Drivers spent 9–10% more time scanning for the bicyclist in the side mirror with the S1 treatment than they did with the S0 treatment.

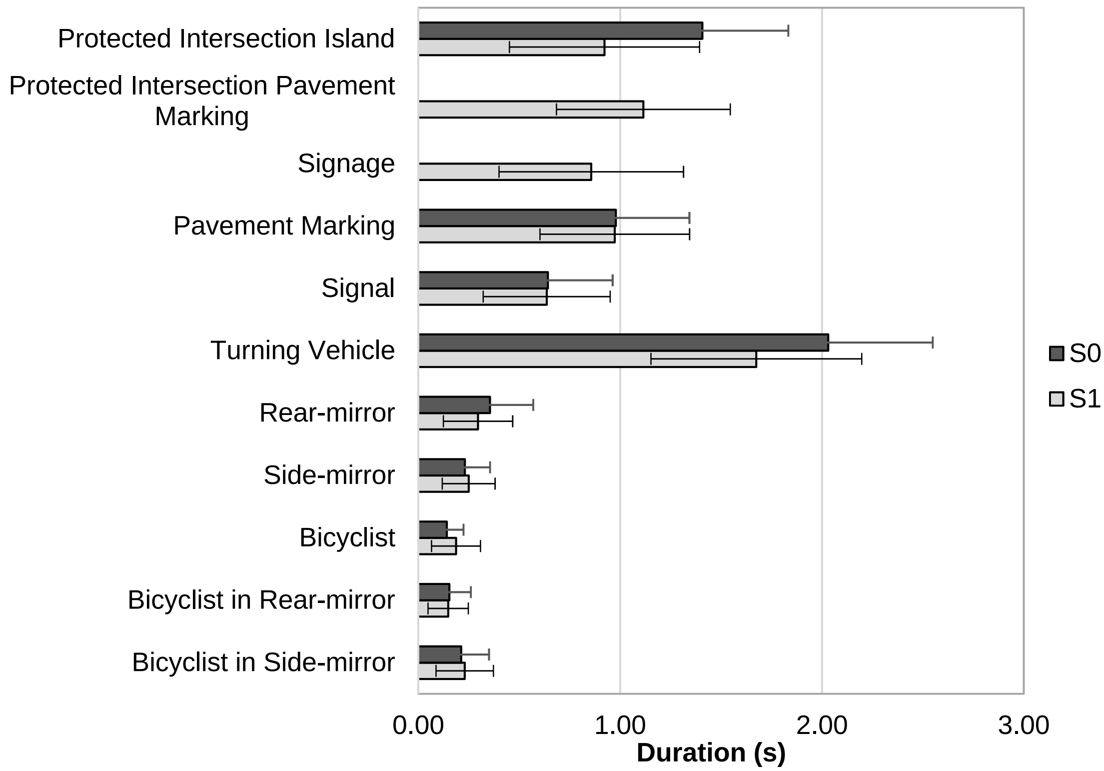


Fig. 5. Bar plots of ATFD (s) for signage treatment levels.

This result indicates that the S1 treatment may positively influence driver behavior. The message of the sign may alert the driver that they should be actively looking for a bicyclist while approaching the intersection. This may also be enhanced by the trend of the driver's visual path towards the right side of the road when the S1 treatment is present. The driver is already looking in that direction, and it may feel natural to continue moving the visual scanning path to the right, towards the passenger side mirror. This possibility would also explain the 14% reduction in ATFD for the Rear Mirror AOI with the presence of additional signage (0.30 vs. 0.35 s).

The only statistically significant difference in ATFDs occurred for the Turning Vehicle AOI (two-tailed p-value = 0.001 for S0 vs. S1). Motorists spent less time fixating on oncoming turning vehicles with the S1 treatment than they did with the S0 treatment (1.85 vs. 2.16 s). This change could influence the ATFDs for bicyclist-related AOIs, in that a greater portion of their visual attention could have been allocated to the ATFDs for those bicyclist-related AOIs. However, all of the bicyclist-related AOIs either decreased or remained the same. ANOVA revealed that fixations on the oncoming turning vehicles had statistically significant differences in ATFDs ($p = 0.001$). No other statistically significant differences were found.

4.2. Crash avoidance

We evaluated treatments with respect to crash avoidance by analyzing simulator output data collected while participants drove through 22 right-turning intersections. The primary objective of this experiment was to determine how well motorists were able to detect the potential hazard (i.e., bicyclist in the adjacent bicycle lane) and avoid a crash with the bicyclist while performing the right-turn maneuver. Crash avoidance was measured by considering motorists who could not avoid a near-collision or collision with the through-moving adjacent bicyclist lane. The bicyclist approaching the intersection from behind the motorist was entirely within the motorist’s blind spot. The participant could avoid collision by detecting the bicyclist in the rear or side mirror. The three-dimensional display in the driving simulator did not show vehicles immediately to the right of the motorist, and participants had a larger blind spot than in a real driving environment (Gugerty, 1997). Placement of the bicyclist in the experimental coding was such that the motorist would likely hit the bicyclist approaching from the vehicle’s blind spot unless the bicyclist was detected in the mirrors (i.e., a worst-case loading situation).

Motorist crash-avoidance behavior was observed during every right-turn maneuver. Motorists driving in the simulated environment were observed continuously from the simulator’s operator station and by the participant’s head-mounted mobile eye-tracker. Eye-tracker video records were analyzed, and the crashes and near-collisions were noted. Recorded crash data were validated by checking the locations of the subject vehicle and bicycle centroids, recorded as dynamic variable data in the driving simulator. We assessed crash avoidance behavior using descriptive statistics and statistical analysis, similarly to the prior driver measures.

During the 616 right turns, 75 incidents (47 near-collisions and 28 collisions) were made across 21 treatments by 20 participants. Thirteen participants (65%) crashed more than once. Crash factors comprised both environmental and motorist factors; however, only environmental factors were assessed for this study. TTC was calculated for right-turn maneuvers that resulted in incidents. Traffic conflicts between a right-turning motorist and a through-moving bicyclist were defined as instances when a collision would be imminent if the trajectories remained unchanged. TTC was calculated when the centroid of the turning vehicle crossed the bicycle's path. Because the bicycles were coded to have constant speed, this measure of the TTC value was fixed (i.e., there was no dynamic nature of the TTC value as neither actor could adjust the collision course). Because TTC was calculated from the vehicle centroid, our results are not necessarily comparable to other experiments with more careful calculation of TTC values from vehicle edge to vehicle edge. Results showed that 57% of traffic conflicts had TTCs equal to or less than 1.5 s (Fig. 6).

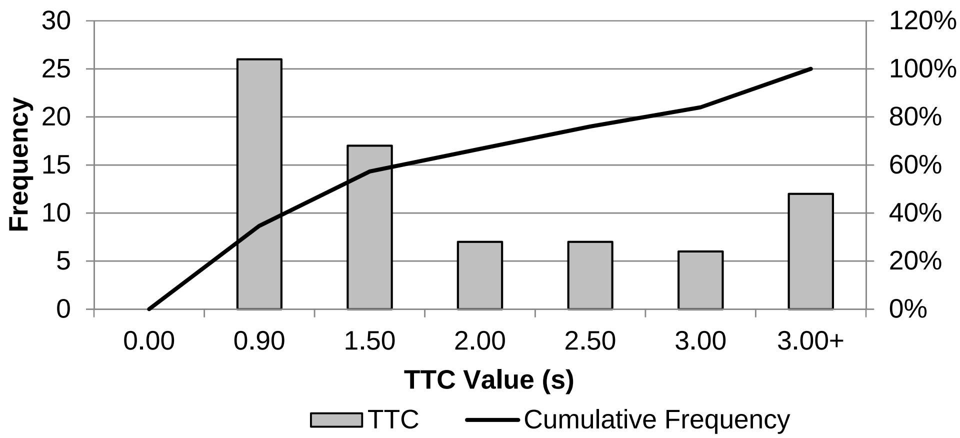


Fig. 6. TTC frequency and cumulative frequency distributions for all incidents.

The risk of collision (ROC) score was determined by classifying TTCs of 0.0–0.9 s as "high risk" and TTCs of 1.0–1.5 s as "moderate risk". According to the TTC threshold values and ROC scores, only 26 of the 75 incidents had high-risk (n = 8) or moderate-risk (n = 18) TTC values (Brown, 1994; Gettman et al., 2008; Sayed et al., 1999).

The dataset was split by the four independent treatment variables, to isolate their individual impact. Frequency and cumulative frequency distributions were plotted for the various treatment levels. Cumulative frequency represents the percentage of incidents with TTCs below 0.9 or 1.5 s (as specified) among the total number of incidents at a specific treatment level. All treatments had incidents with TTC values greater than 1.5 s; however, for brevity, not all results are shown here. As an example, Fig. 7 shows frequency and cumulative frequency distributions for the curb radius treatment levels (C0, 30-ft. curb radius and C1, 10-ft. curb radius).

A Chi-square test was performed for treatments to test for any statistically significant differences between ROC scores of the various treatment levels. Because the ROC scores were directly calculated from the TTC values, this statistical analysis reflects the significance of differences in the TTC value bins within the frequency and cumulative frequency distributions. No statistically significant differences were found at the 95% confidence level (Table 6).

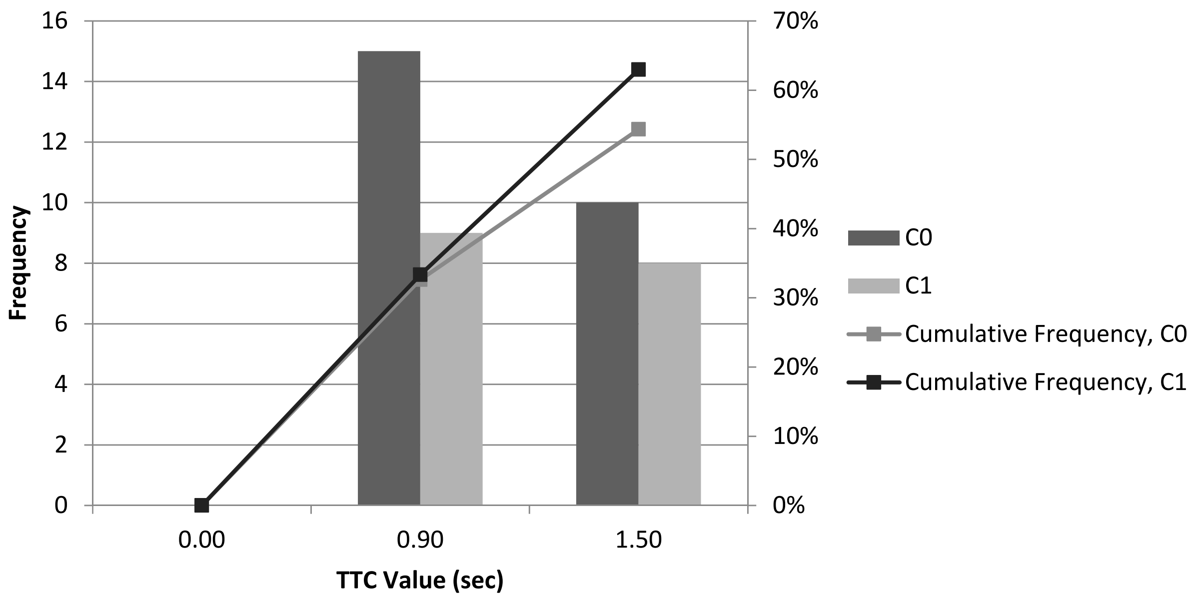


Fig. 7. TTC frequency and cumulative frequency distributions, by curb radius treatment level.

Table 6

Summary of Statistical Analysis for ROC Scores of Near-collisions and Collisions.

Treatment Levels Compared		p-value	Significant
S0	S1	0.92	No
PM0	PM1	0.45	No
PM0	PM2	0.97	No
PM0	PM3	0.24	No
PM0	PM4	0.65	No
C0	C1	0.38	No
PI0 (T1)	PI1	0.73	No
PI0 (T11)	PI2	0.56	No
PI1	PI2	0.66	No

4.2.1. Discussion

For the crash avoidance metric, protected intersection designs had the greatest effect on behavior but showed an inconsistent pattern of change. Protected intersection treatment levels were unique because the treatment was not fully counterbalanced with the other treatments. PI0 (T1) and PI0 (T11) corresponded to base intersection treatments with 30-ft. curb radius and no pavement marking, without (T1) or with signage (T11). PI1 and PI2 were protected intersection treatments with islands and 30-ft. curb radius, either with no signage and no pavement marking (PI1) or with signage and green pavement marking (PI2). Figure 8 demonstrates the frequency and cumulative frequency distributions for protected intersection treatment levels.

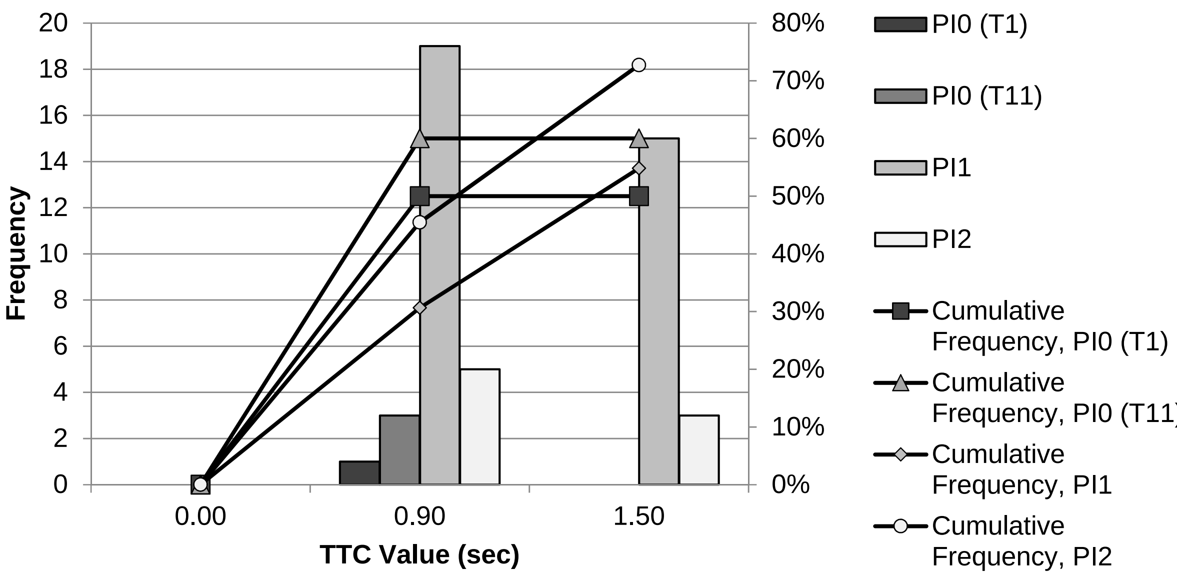


Fig. 4. TTC frequency and cumulative frequency distributions by protected intersection treatment level.

Cumulative frequencies of high-risk TTC values (≤0.9 s) were lower with PI1 vs. PI0 (T1) (31% vs. 50%) and with PI2 vs. PI0 (T11) (45% vs. 60%), but cumulative frequencies of moderate- and high-risk TTC values (≤1.5 s) were higher with PI1 vs. PI0 (T1) (55% vs. 50%)

and PI2 vs. PI0 (T11) (73% vs. 60%). Chi-square test results revealed no statistically significant differences at the 95% confidence level (Table 6). Overall, the impact of the protected intersection treatment on crash avoidance behavior was inconsistent. However, the reduction in high-risk TTC values could indicate that the physical separation of the barrier island at the corner of the protected intersection creates more space/time between the driver and bicyclist.

4.3. Potential crash severity

Treatments were evaluated with respect to potential crash severity to determine the effects of selected engineering treatments on the velocity of motorists when a near-collision or collision occurs with the bicyclist during the right-turn maneuver. Bicyclists traveled at the same velocity (16 mph) throughout the experiment, but the vehicle velocities varied across participants and treatments. For this potential crash severity analysis, the only velocities considered were those of vehicles at the time of moderate- or high-risk traffic conflicts (determined by the TTC values). Higher velocities at the time of the traffic conflict were considered to be more severe.

Figure 5 displays a boxplot and scatterplot distribution of the vehicles velocities across all of the moderate- and high-risk incidents. As can be seen in the figure, there is a single outlier in this data (with a velocity equal to 5.03 mph). This outlier was removed for calculation of the mean and range values of the vehicle velocities, which are summarized in Table 7. The mean velocity for these “moderate risk” and “high risk” incidents was 12.70 mph and the range of the vehicle velocities was 8.57 mph.

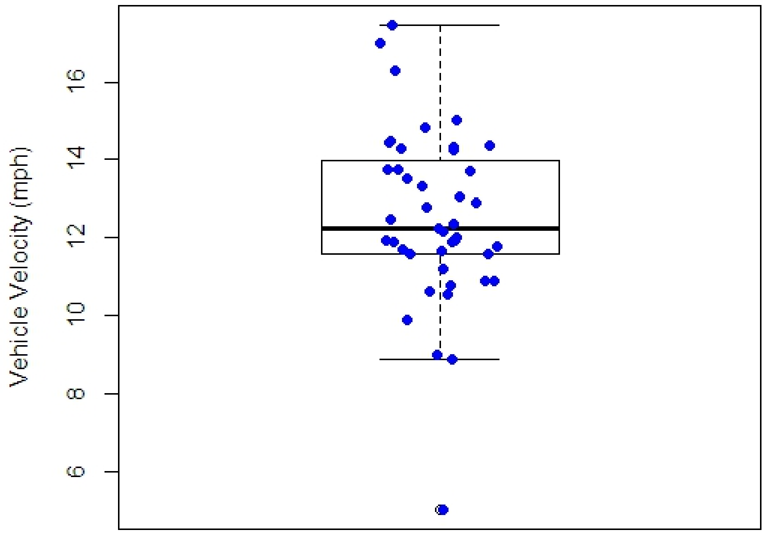


Figure 5 Boxplot and scatterplot of vehicle velocities for all moderate- & high-risk incidents

A two-sample Welch's t-test and the ANOVA analysis were performed to compare the zero-level with non-zero treatment levels. Table 7 displays mean velocities of the moderate- and high-risk incidents for the treatment levels and the resulting p-values. The PI0 (T1) treatment had only one moderate- to high-risk incident; thus, statistical tests could not be performed. No statistically significant differences were found at the 95% confidence level.

Table 7

Summary of Statistical Analysis for Vehicle Velocities of Near-collisions and Collisions.

Treatment Levels Compared		Vehicle Velocities (mph)		p-value	Significant
S0	S1	12.53	12.50	0.96	No
PM0	PM1	11.76	12.99	0.17	No
PM0	PM2	11.76	13.03	0.22	No
PM0	PM3	11.76	14.98	0.23	No
PM0	PM4	11.76	12.08	0.69	No
C0	C1	12.62	12.33	0.63	No
PI0 (T1)	PI1	14.27	9.78	N/A	N/A

PI0 (T11)	PI2	12.86	11.53	0.43	No
PI1	PI2	9.78	11.53	0.58	No

4.3.1. Discussion

For the crash potential metric, curb radius treatments had the most effect on behavior. This treatment is particularly important for the potential crash severity measurement, as a smaller curb radius generally requires a slower turning velocity. Fig. **6** displays a boxplot and scatterplot distribution of the vehicle velocities across all moderate- and high-risk incidents for the curb radius treatment levels (C0, 30-ft. curb radius and C1, 10-ft. curb radius). The single outlier in the C0 data (velocity = 5.03 mph) was removed for the calculation of the mean and range values of the vehicle velocities for this treatment level.

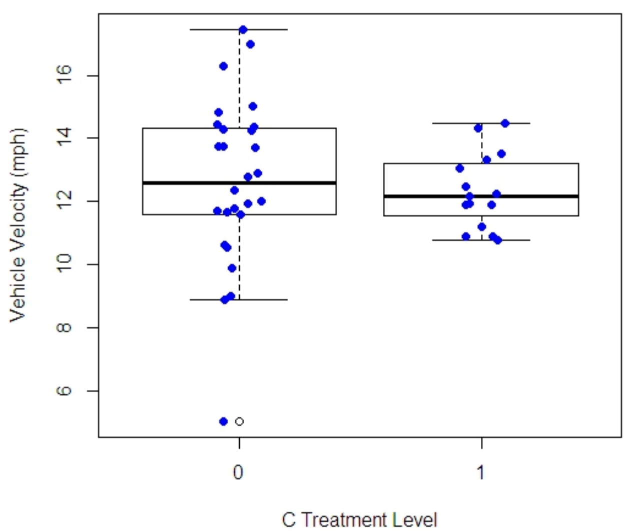


Fig. 6. Boxplot and scatterplot of vehicle velocities for curb radius treatment levels.

The C1 radius treatment led to a 4% smaller mean vehicle velocity (12.33 mph) and a 54% smaller range of vehicle velocities (10.76–14.47 mph; difference: 3.71 mph) than the C0 radius treatment (mean: 12.90 mph; range: 8.88 – 16.98 mph; range difference: 8.10 mph). This reduction in vehicle velocities, while anticipated due to the fundamental concepts of geometric design, is a clear safety benefit. Lowering the speeds of turning vehicles by any amount will reduce the severity of a potential collision. P-values for the ANOVA analysis and Welch's t-test were both 0.63. Thus, there were no statistically significant differences between C0 and C1, as measured by vehicle velocities at the time of the incident, at the 95% confidence level.

5. Conclusions

5.1. Overall findings from this study

This research evaluated the effects of design treatments (supplemental signage, intersection pavement marking, curb radius, and protected intersection design) on motorist behavior using three different motorist performance measures: visual attention of motorists, their crash avoidance behavior, and the potential severity of the near-collision or crash, as measured by the motor vehicle speed. All performance measures were assessed during right-turn maneuvers that occurred during the latter portion of the green phase at signalized intersections with a shared right-turn and through lane, under the highest driver-loading scenario identified in our prior experiment. Most of the differences were not statistically significant; however, the lack of a statistically significant effect for a particular treatment does not necessarily mean that the treatment will not have an effect on safety. Our interpretations of the data and recommendations, with respect to the four treatment types, follow.

5.1.1. Signage treatments

Findings of this experiment indicated that the level-one signage treatment, the ODOT OR10-15b “Turning Vehicles Yield to Bicycles” symbol sign (Table 1), is an effective method of positively influencing driver behavior with respect to visual attention. We found a generally positive pattern of change in visual attention with the addition of the sign. Participants increased the amount of time spent scanning the side mirror for the bicyclist by 9% and the side mirror when in close proximity to the intersection (i.e. when the bicyclist is visible within the side mirror) by 10% compared to the level-zero signage treatment.

5.1.2. Pavement marking treatments

We found mixed results with respect to the influence of pavement markings on changes in driver behavior. The presence of through intersection markings improved measured driver performance in the visual search and crash avoidance spectrums. Although all tested designs had some positive effects, our evidence suggested that either the single or double dotted white bike line with bicycle stencil pavement marking (level-one or level-two treatment) should be considered. The addition of green markings, commonly associated with bicycles, did not change the driver’s visual attention as much as the simpler, white dotted line markings.

5.1.3. Curb radius treatments

The smaller curb radius treatment (10-ft. radius, level-one treatment in Table 1) appears to be an effective method of positively influencing driver behavior, with respect to crash avoidance and potential crash severity. We found a generally positive pattern of change in potential crash severity with the addition of the smaller curb radius, with a 4% decrease in mean vehicle velocity during moderate- to high-risk incidents compared to the larger curb radius. With the level-one curb radius treatment, the range of vehicle velocities was 54% less than the range with the level-zero treatment. This finding of lower speeds is consistent with the formulaic relationship between the design speed and the minimum radius of curvature, found in “A Policy on Geometric Design of Highways and Streets” of the American Academy of State Highway and Transportation Officials (AASHTO, 2011).

5.1.4. Protected intersection treatments

Protected intersection treatments included no protected intersection (level zero), protected intersections with islands (level one), and protected intersections with islands and green pavement markings (level two) (Table 1). Level-one protected intersection treatment appears to be an effective method of positively influencing driver behavior with respect to potential crash severity. We did not find a consistent pattern of change in crash avoidance with the addition of the protected intersection with islands. Level-one treatment led to a 19% lower cumulative frequency of high-risk TTC values (≤0.9 s) and 5% higher cumulative frequency of moderate- and high-risk TTC values (≤1.5 s) than the level-zero protected intersection treatment.

We did not find the level-two protected intersection treatment to be a consistently effective method of positively influencing driver behavior. We did not observe a consistent pattern of change in crash avoidance with the addition of the protected intersection with islands and green pavement markings. This treatment resulted in a 15% lower cumulative frequency of high-risk TTC values and 13% higher cumulative frequency of moderate- and high-risk TTC values than the level-zero protected intersection treatment. Frequencies of moderate- and high-risk TTCs with the level-two treatment were significantly lower than with the level-one protected intersection treatment (5 vs. 19 and 3 vs. 15, respectively).

5.2. Recommendations

Every treatment had some positive measurable effect on driver performance. The presence of signage improved driver performance across the visual attention spectrum. The sign attracted the driver's attention and resulted in more frequent searching for bicyclists. Given its relatively low cost, the "Turning Vehicles Yield to Bicycles" sign should be installed where feasible. To maximize the effect, the sign should be installed in a location most visible to drivers and in advance of the turning-merge conflict area. Use of a smaller curb radius produced decreases in the vehicle turning speed and the number of high-risk conflicts. The reduction in vehicle turning speed was expected but is a clear measured benefit for safety. Pavement markings, particularly the simplest dotted markings, also improved most driver behaviors. We did not observe sufficiently significant changes to recommend the use of additional green markings; however, our results are not conclusive and we do not intend that our recommendation be construed to suggest that the green markings not be installed.

Protected intersections with an island and/or green pavement marking would require further design work. The consideration of many issues (e.g., constructability issues, truck turning/mountable curbs, reflective markings on curbs for visibility at night, and accommodation of pedestrians) was outside the scope of this study. Nonetheless, the protected intersection designs did show some improvements in driver performance with respect to the potential crash severity as measured by vehicle speeds in near and actual collisions. This finding correlates with the curb radius treatment. The protected intersection design differs from other treatments in that it moves the conflict point between the car and bicycle forward in the intersection. Finally, unlike the other treatments, the protected intersection was a novel design that was not familiar to any driver.

5.3. Limitations and future work

This research provides valuable insights on the causal factors of right-hook crashes during the latter portion of the green phase at signalized intersections. Although various driver performance metrics can be measured robustly, it is not yet clear how to map the magnitudes of differences to expected crash outcomes. One fundamental limitation of the within-subject design is fatigue effects, which can cause the participant's performance to decline over time during the experiment. Participants might get tired or bored as the experiment progresses. Furthermore, repeated right-turning maneuvers pose the threat of inducing simulator sickness more frequently than through movements in simulated driving. To reduce the risks of fatigue effect and simulator sickness, the experiment could be conducted in two trials on two different days.

Another limitation associated with this study is related to the statistical power of the analyses. According to post-hoc power calculations, limited statistical power was observed which could be due to the limited number of observations.

Oregon driving code and practices involve striping bicycle lanes all the way to the intersection, which differ from practices in other states. Drivers living in Oregon will likely understand these designs, which might differ for drivers elsewhere. The experiment could be conducted in other states to see whether these and other behavioral differences exist. Finally, this experiment measured the performance of individual treatments, either alone or in combination with other treatments. No analysis was performed to identify the optimal combination.

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References

American Association of State Highway and Transportation Officials (AASHTO), 2011. Equation 3-8, A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials, Washington D.C., pp. 3-31.

Brady, J., J. Loskorn, A. Mills, J. Duthie, and R. Machemehl, 2011. Operational and Safety Implications of Three Experimental Bicycle Safety Devices in Austin, TX. In 2011 TRB Annual Meeting Compendium of Papers. CD-ROM. Transportation Research Board of the National Academies, Washington, D.C.

Brown, G. R. Traffic conflicts for road user safety studies, 2011. *Canadian Journal of Civil Engineering*, Vol. 21, No. 1, pp. 1-15. http://dx.doi.org/10.1139/l94-001

Caird, J., S. Milloy, A. Ohlhauser, M. Jacobsen, M. Skene, and J. Morrall, 2008. Evaluation of Four Bicycle Lane Treatments Using Driving Simulation: Comprehension and Driving Performance Results. Annual Conference of Canadian Road Safety Professionals, Whistler, British Columbia.

City and County of San Francisco Municipal Transportation Agency, 2010. Evaluation of Solid and Dashed Green Pavement for Bicycle Lanes: Request to Experiment. City and County of San Francisco Municipal Transportation Agency.

City of Columbia, 2009. Request to Experiment: Use of Colored Pavement Markings on On-Street Bikeways. City of Columbia, Missouri Non-Motorized Transportation Pilot Program.

City of New York, 2005. Evaluation of Solid Green Bicycle Lanes to Increase Compliance and Bicycle Safety: Request to Experiment. City of New York, Department of Transportation.

City of Portland, 2012. Progress Report: Request to Experiment "9-105(E)- Colored Bike Lanes and Bike Boxes- Portland, OR." City of Portland.

Department for Transport, 2008. Local Transport Note: Cycle Infrastructure Design. Department for Transport, The Stationary Office (TSO), London.

Falbo, N, 2014. Protected Intersections for Cyclists. https://vimeo.com/86721046. Accessed September 2014.

Federal Highway Administration (FHWA), 2009. Manual on Uniform Traffic Control Devices. Federal Highway Administration.

Federal Highway Administration (FHWA), 2009. MUTCD- Interim Approval for Optional Use of Green Colored Pavement for Bike Lanes (IA-14). Federal Highway Administration, 2011.

Fisher, D. L., A. Pollatsek and W. J. Harrey, 2011. Eye Behaviors: How Driving Simulators can expand their Role in Science and Engineering. *Handbook of Driving Simulation for Engineering, Medicine, and Psychology,* CRC Press.

Gettman, D., L. Pu, T. Sayed, and S. Shelby, June 2008. *Surrogate Safety Assessment Model and Validation: Final Report*. FHWA-HRT-08-051, Federal Highway Administration (FHWA), Washington D.C.

Goeverden, K. V., and T. Godefrooij, 2011. The Dutch Reference Study: Cases of interventions in bicycle infrastructure reviewed in the framework of Bikeability. University of Copenhagen.

Green, P, 2007. Where do drivers look while driving (and for how long)? In R. E. Dewar & R. Olson (Eds.), In *Human factors in traffic safety*, 2nd ed., Tucson, AZ: Lawyers & Judges Publishing, pp. 57-82.

Gugerty, L. J., 1997. Situation awareness during driving: Explicit and implicit knowledge in dynamic spatial memory. *Journal of Experimental Psychology: Applied*, Vol. 3, No. 1, pp. 42-66. http://dx.doi.org/10.1037/1076-898X.3.1.42

Hunter, W., R. Srinivasan, and C. Martell, 2008. St. Petersburg's Green Bike Lane Weaving Area: An Evaluation. Florida Department of Transportation and University of North Carolina, Chapel Hill.

Hurwitz, D., C. Monsere, M. Jannat, J. Warner, and A. Razmpa, 2015. Towards Effective Design Treatment for Right Turns at Intersections with Bicycle Traffic. Oregon Department of Transportation (ODOT).

Institute of Transportation Engineers (ITE), 2004. Toolbox on Intersection Safety and Design. Institute of Transportation Engineers.

Massachusetts Department of Transportation (MassDOT), 2015. Separated Bike Lane Planning & Design Guide. Massachusetts Department of Transportation.

Mead, J., A McGrane, C. Zegeer, and L. Thomas, 2014. Evaluation of Bicycle-Related Roadway Measures: A Summary of Available Research. Federal Highway Administration (FHWA).

National Association of City Transportation Officials (NACTO), 2011a. *Urban Bikeway Design Guide*. National Association of City Transportation Officials. http://nacto.org/cities-for-cycling/design-guide/. Accessed May 30, 2013.

National Association of City Transportation Officials (NACTO), 2011b. *Urban Street Design Guide*. National Association of City Transportation Officials. http://nacto.org/cities-for-cycling/design-guide/. Accessed May 30, 2013.

National Association of City Transportation Officials (NACTO), 2013. *Urban Street Design Guide*. The National Association of City Transportation Officials. http://nacto.org/usdg/intersection-design-elements/. Accessed April 20, 2015.

National Highway Traffic Safety Administration (NHTSA), 2011. Traffic Safety Facts 2011: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System. Publication DOT HS 811 754. U.S. Department of Transportation, National Highway Traffic Safety Administration. http://www-nrd.nhtsa.dot.gov/Pubs/811754AR.PDF. Accessed May 30, 2013.

National Highway Traffic Safety Administration (NHTSA), 2013. Bicyclists and other cyclists. National Highway Traffic Safety Administration, Washington, D.C. http://www-nrd.nhtsa.dot.gov/Pubs/811743.pdf. Accessed on April 20, 2015.

Oregon Department of Transportation (ODOT), 2011. *Oregon Bicycle and Pedestrian Design Guide*. Oregon Department of Transportation, Pedestrian and Bicycle Program.

Oregon Department of Transportation (ODOT), 2013. Sign Policy. Oregon Department of Transportation, Traffic Roadway Section. http://www.oregon.gov/ODOT/HWY/TRAFFIC-ROADWAY/pages/sign_policy.aspx. Accessed April 10, 2015.

Pedestrian and Bicycling Information Center (PBIC), 2002. Chicago Bike Lane Design Guide. Pedestrian and Bicycling Information Center. http://nacto.org/wp-content/uploads/2011/03/Chicago-Bike-Lane-Design-Guide-2002.pdf. Accessed April 15, 2015.

Pucher, J., C. Komanoff, and P. Schimek. Bicycling Renaissance in North America?: Recent Trends and Alternative Policies to Promote Bicycling. *Transportation Research Part A: Policy and Practice*, Vol. 33, No. 7, 1999, pp. 625-654.

Pucher, J., and R. Buehler. Why Canadians Cycle More than Americans: A Comparative Analysis of Bicycling Trends and Policies. *Transport Policy*, Vol. 13, No. 3, 2006, pp. 265-279.

Pucher, J., R. Buehler, and M. Seinen. Bicycling Renaissance in North America? An Update and Re-appraisal of Cycling Trends and Policies. *Transportation Research Part A: Policy and Practice*, Vol. 45, No. 6, 2011, pp. 451-475.

Sayed, T. and S. Zein. Traffic conflict standards for intersections, 1999. Transportation Planning and Technology, Vol. 22, No. 4, pp 309-323. http://dx.doi.org/ 10.1080/03081069908717634

Singh, R., S. Turner, T. Hughes, and G. Nates, 2011. Safety at traffic signals for cyclists and pedestrians. In Proceedings of the IPENZ Transportation Group Conference. Institute of Professional Engineers New Zealand (IPENZ), Auckland.

Sundstrom, C., and D. Nabors, 2014. BIKESAFE 2014: Bicycle Safety Guide and Countermeasure Selection System. Federal Highway Administration (FHWA).

Warnock, F, 2010. Bikes Lanes Through Intersections Survey Results. Bike Delaware. http://www.bikede.org/2010/11/07/bike-lanes-through-intersections-survey-results/. Accessed on April 10, 2015.