TOWARDS EFFECTIVE DESIGN TREATMENT FOR RIGHT TURNS AT INTERSECTIONS WITH BICYCLE TRAFFIC

Final Report

SPR 767

Oregon Department of Transportation

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16. Abstract

The overall goal of this research was to quantify the safety performance of alternative traffic control strategies to mitigate right-turning vehicle-bicycle crashes at signalized intersections in Oregon. The ultimate aim was to provide useful design guidance to potentially mitigate these collision types at the critical intersection configurations. This report includes a comprehensive review of more than 150 scientific and technical articles that relate to bicycle-motor vehicle crashes. A total of 504 right-hook crashes were identified from vehicle path information in the Oregon crash data from 2007-2011, mapped and reviewed in detail to identify the frequency and severity of crashes by intersection lane configuration and traffic control. Based on these efforts, a two stage experiment was developed in the OSU high-fidelity driving simulator to investigate the causal factors of right-hook crashes at signalized intersections with a striped bike lane and no right-turn lane, and to then identify and evaluate alternative design treatments that could mitigate the occurrence of right-hook crashes. Experiment 1 investigated motorist and environmental related causal factors of right-hook crashes, using three different motorist performance measures: 1) visual attention, 2) situational awareness (SA) and 3) crash avoidance behavior. Data was collected from 51 participants (30 male and 21 female) turning right 820 times in 21 different experimental scenarios. It was determined that the worst case right-hook scenario occurred when a bicycle was approaching the intersection at a higher speed (16 mph) and positioned in the blind zone of the motorist. In crash and near crash situations (measured by time-to-collision) the most common cause was a failure of the driver to actively search for the adjacent bicyclist (situational awareness level 1), although failures were also determined to occur due to failures of projection (i.e. incorrectly assuming that the bicycle would yield or that there was enough time to turn in front of the bicycle). Elements of driver performance and gap acceptance collected in the first stage simulator experiment were field validated to provide additional confidence in the findings. The research reviewed 144 hours of video and identified 43 conflicts where the time-to-collision (TTC) measured less than 5 seconds. When field observations of scenarios most similar to those in the simulator were isolated, the analysis indicated that the distribution of the TTCs values observed in the simulator were consistent with those observed in the field. Experiment 2 evaluated several possible design treatments, (specifically: signage, pavement markings, curb radii, and protected intersection designs), based on the visual attention of motorist, their crash avoidance behavior, and the severity of the observed crashes. Data was collected from 28 participants (18 male and 10 female) turning right 596 times in 22 scenarios that were used. The resulting analysis of the driver performance indicators suggest that while we can measure the various driver performance metrics robustly, and all of the treatments had some positive effect on measured driver performance, it is not yet clear how to map the magnitudes of the differences to expected crash outcomes. Additional work is recommended to address the limitations of this study and to further consider the potential effects of the right-hook crash mitigation strategies from this research.

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Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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TECHNICAL SUMMARY

A comparatively large number of crashes occur at intersections despite the fact that they constitute only a small fraction of the overall area of the surface transportation system. In addition, a variety of modes directly interact, sometimes in conflicting ways with severe outcomes. At intersections without space for both a separate right-turn and bicycle lane, bicyclists are often to the right of motorists as they approach an intersection. Though motorists must legally yield the right-of-way to bicyclists in bicycle lanes (in Oregon), motorists often fail to search for bicyclists, search but don't notice approaching bicyclists, or misjudge the gap of the approaching bicyclist. In addition, bicyclists do not always position themselves to be readily seen or approach at high rates of speed.

Bicycle-motor vehicle crashes involving right-turning vehicles and through-moving bicycles have been typed as "the right-hook." Right-hook crashes describe a type of bicycle-motor vehicle crash that occurs between a right-turning vehicle and a through-moving bicycle.

The overall goal of the research was to quantify the safety performance of alternative traffic control strategies to mitigate right-turning vehicle-bicycle crashes at signalized intersections in Oregon. The ultimate aim was to provide useful design guidance *(NACTO 2011)* to potentially mitigate these collision types at the critical intersection configurations. Thus, the objectives of the research were:

1. To comprehensively analyze the literature and to develop an understanding of the known crash mechanisms;

2. To analyze Oregon crash records and to develop an understanding of the frequency of the crash problem at Oregon intersections and guide the design of the simulator experiment;

3. To address the identified gaps in the literature and develop a fundamentally better understanding of driver and bicyclist interactions during right-turning events at signalized intersections in a driving simulator;

4. To validate the driver performance and gap selection in the driving simulator with field observations; and

5. To evaluate potential design treatments through the observation of driver performance in a driving simulator.

To accomplish these objectives the research team followed a robust research plan. First, a comprehensive review of more than 150 scientific and technical articles was performed. Then a total of 504 potential right-hook crashes were identified in the Oregon reported crash data from 2007-2011 and reviewed in detail. Based on these efforts, a two-stage experiment was developed in the Oregon State University (OSU) high-fidelity driving simulator to investigate the causal factors of right-hook crashes, and to then identify and evaluate alternative design treatments that could mitigate the occurrence of right-hook crashes. Elements of driver performance and gap acceptance collected in the first-stage simulator experiment were field validated to provide additional confidence in the findings.

T.3.0 Analysis of Potential Right-hook Crashes in Oregon

The research reviewed 504 right-hook crashes identified from vehicle movement data out of the 4,072 total crashes identified in Oregon Department of Transportation (ODOT) bicycle crash data (*2007-2011).* Right-hook crashes accounted for 12.3% of all crashes during this time period. The frequency and percentage of right-hook crashes including all variables except injury levels are displayed in the following tree plot (Figure T.3). Though it is a frequent crash type, the majority (62%) of recorded crashes were of moderate severity. A further 28% were minor injury and 4% were no injury. Still, 7% of the crashes were severe or fatal injury and represent an opportunity to improve safety for bicyclists. Each right-hook crash was reviewed in detail to identify the type of intersection traffic control and lane configurations. Intersection locations accounted for 74% of right-hook crashes; the remaining 26% of crashes occurred at driveways. The most common intersection configuration for right-hook crashes was a bike lane to the right of a through motor vehicle lane with no right-turn lane. This configuration accounted for 59% of total crashes at signalized intersections and 64% of total crashes at minor stop intersections.

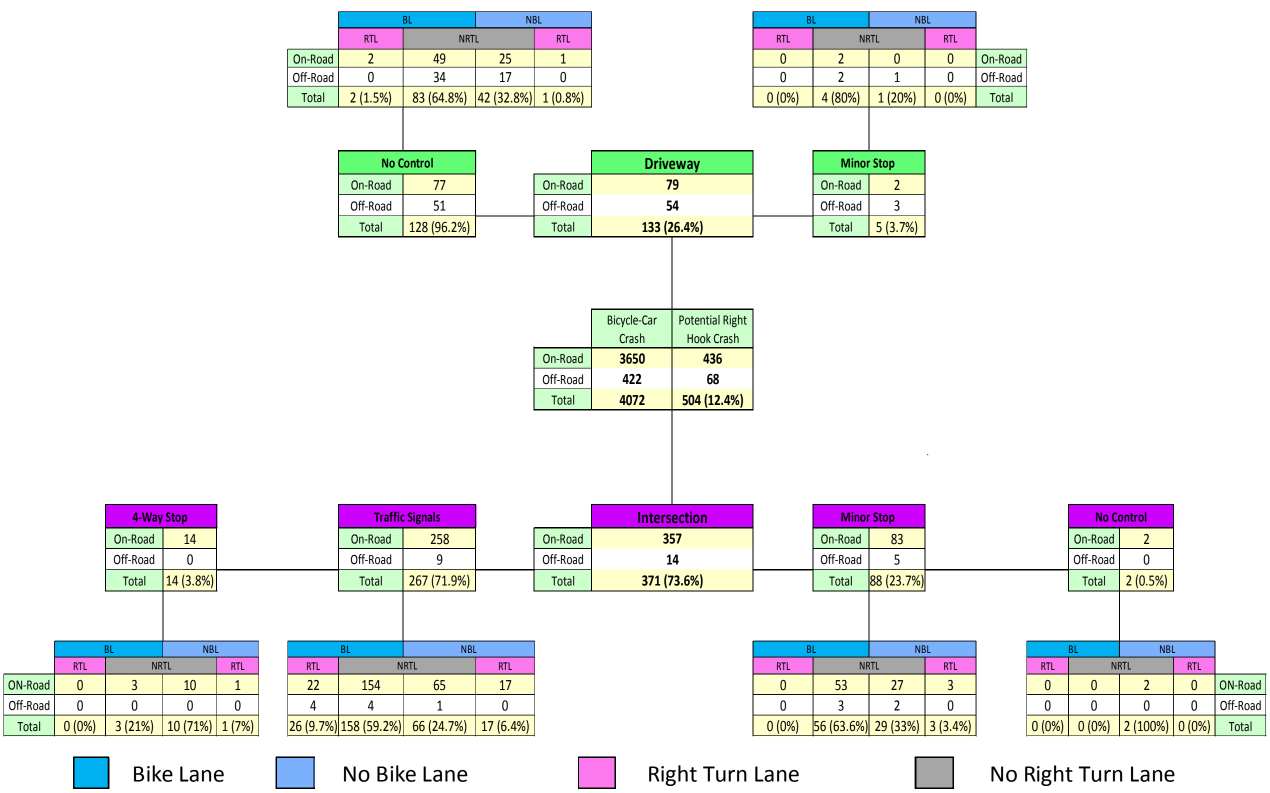


Figure T.1: Tree plot of potential right-hook crashes by traffic control device, the presence of the bike lane, and the presence of right-turn lane.

T.1.0 Experimental Methodology

The OSU driving simulator and an ASL Mobile eye tracker were used to conduct Experiment 1 and 2 (Figure T.2).

Figure T.2: OSU driving simulator (left) Mobile Eye XG recording unit (right)

T.1.1 Simulator Phase I

Experiment 1 consisted of three components, where each component addresses a specific set of research questions: 1) right-turning motorists' visual attention, 2) situational awareness (SA), and 3) crash avoidance behavior. Table T.1 shows different experiment factors and their levels. The factorial design resulted in 24 scenarios for inclusion in the experiment, which were manipulated within subjects.

Table T.1: Experimental factors and levels

Name of the Variable	Category	Levels
Bicyclist relative position	Nominal (Categorical)	None
		One (1) bicyclist riding in front of the motorist in an adjacent bicycle lane to the right
		One (1) bicyclist coming from behind the motorist in an adjacent bicycle lane to the right
Speed of bicyclist	Discrete	Low (12 mph)
		High (16 mph)
Presence of oncoming vehicular traffic	Dichotomous (Categorical)	None
		Three (3) Vehicles
Presence of conflicting pedestrian	Dichotomous (Categorical)	None
		One (1) pedestrian walking towards the motorist

T.1.2 Field Validation

The selection of a location was critical to performing a field validation of the controlled scenarios of bicycle-vehicle interactions found in the driving simulator experiment. After careful search and screening, a location that had similar geometry, significant through bicycles, and right turning vehicle traffic was selected. A total of 144 hours of driver-bicyclist interactions were recorded with dual feed digital cameras installed at an intersection in Portland, OR. A screen capture of the video views used to reduce the conflict is shown in Figure T.3. Approximately one conflict occurred every three hours of video, producing 43 records from the field data that were available for direct comparison to driver performance data from the simulator.

Figure T.3: Screen capture of the video data collection, looking at North Going Street (left) and North Interstate Avenue (right)

T.1.3 Simulator Phase II

The experiment included four independent variables (signage, pavement marking, curb radii, and protected intersections). Each independent variable was either dichotomous or categorical in nature and had either two, three, or five levels (Table T.2). The factorial design resulted in 22 scenarios for inclusion in the experiment, similar to Experiment 1.

Table T.2: Experimental Factors and Levels

Name of the Variable	Acronym	Category	Levels	Levels Descriptions
Signage	S	Dichotomous (Categorical)	0	None
			1	Signage
Pavement Marking	PM	Nominal (Categorical)	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 Radii	C	Discrete	0	Larger curb radii, 30^{ft}
			1	Smaller curb radii, 10^{ft}
Protected Intersection	PI	Nominal (Categorical)	0	None
			1	Protected intersection with islands
			2	Protected intersection with islands and green pavement markings

T.2.0 Participants

For Experiment 1, 67 people (35 male and 32 female) participated in the simulator study. Approximately 24% (11 female and 5 male) of participants reported simulation sickness at various stages of the experiment. All responses recorded from the participants who exhibited simulator sickness were excluded from the original data set. Thus, the final data set was comprised of 51 participants; 30 male (45% of total) and 21 female (31% of total). In Experiment 2, 46 participants were recruited. A higher rate of simulator sickness was observed (39%). Thus, the final data set consisted of 18 male and 10 female drivers. Table T.3 demonstrates the participants' demographics of this simulator experiment. All participants were licensed drivers who reside in the state of Oregon.

Table T.3: Participant Demographics

		Experiment 1		Experiment 2	
Category	**Possible Responses**	**Number of Participants**	**Percentage of Participants**	**Number of Participants**	**Percentage of Participants**
What is your highest completed level of education?	High School Diploma	2	4 %	1	4%
	Some College	17	33 %	13	46%
	Associates Degree	6	12 %	0	0%
	Four-year Degree	13	25 %	10	36%
	Master's Degree	11	22 %	3	11%
	PhD Degree	2	4 %	0	0%
	Other	0	0 %	1	4%
How many years have you been licensed?	1 - 5 years	19	37%	13	46%
	6 - 10 years	14	27 %	4	14%
	11 - 15 years	4	8 %	0	0%
	16 - 20 years	2	4%	2	7%
	More than 20 years	12	24 %	9	32%
What corrective lenses do you wear while driving?	Glasses	0	0 %	2	7%
	Contacts	13	25 %	10	36%
	None	38	75%	16	57%
Do you experience motion sickness?	Yes	6	12 %	4	14%
	No	45	88 %	24	86%
Gender	Male	30	59 %	18	64%
	Female	21	41 %	10	36%
Age	Minimum	Average	Maximum	Average	Maximum
	19	30.24	69	38.04	70

T.4.0 Crash Causation Mechanisms

The first driving simulator experiment investigated motorist- and environment-related causal factors of right-hook crashes, using three different motorist performance measures: 1) visual attention, 2) situational awareness (SA), and 3) crash avoidance behavior. As such, the driving simulator experiment was divided into three components to address specific sets of research questions associated with each performance measure. All performance measures were assessed during right-turn maneuvers that occurred during the latter portion of the green phase at signalized intersections. Figure T.4 summarizes the key areas of interest (AOIs) that were examined. This section summarizes the findings from each component for Experiment 1.

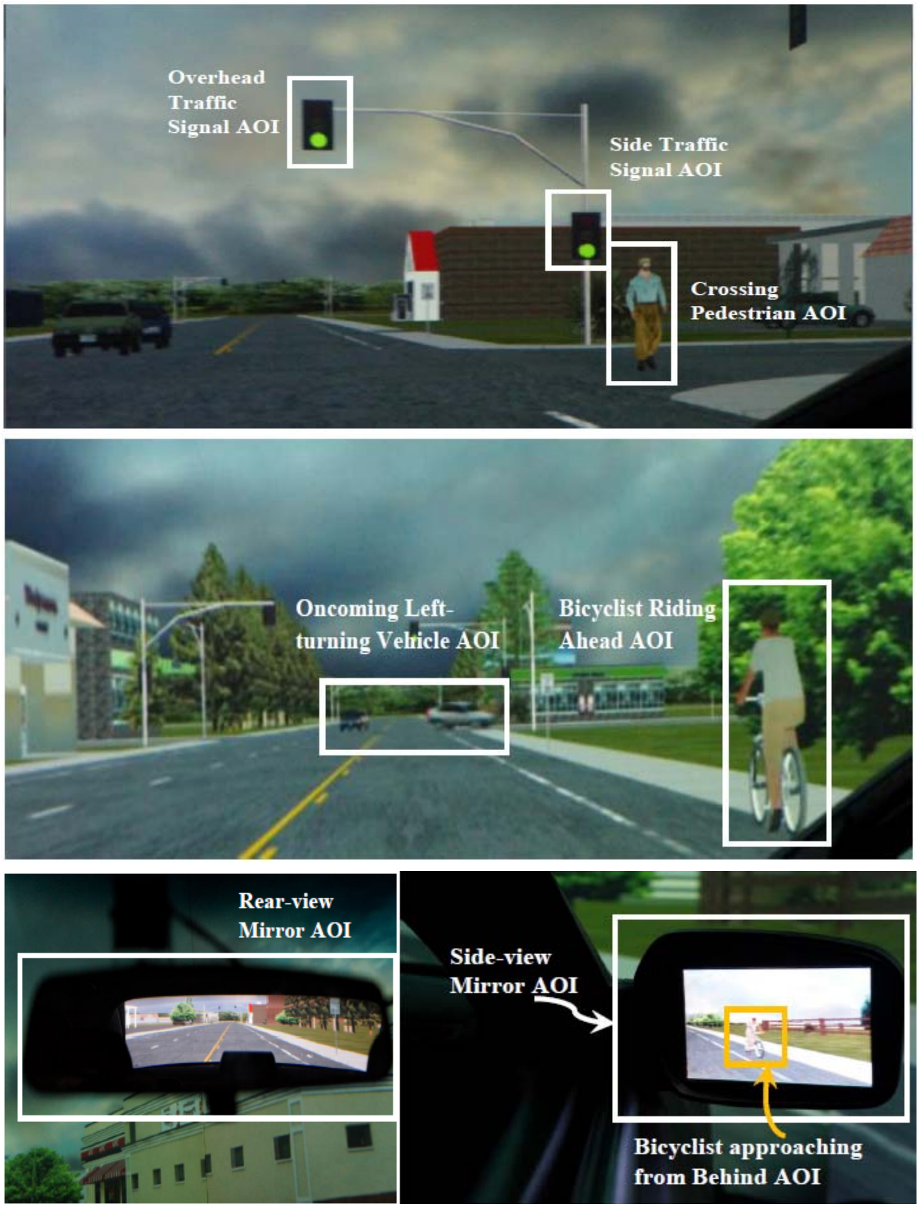


Figure T.4: Key AOI in Experiment 1

T.4.1 Visual Attention

Motorists' visual attention was investigated during 20 right-turning scenarios with bicycle traffic using head-mounted eye-tracking technology. The research objective was to investigate whether motorists actively search for bicyclists before turning right and to examine the influence of various adjacent traffic configurations, such as a pedestrian in the conflicting crosswalk and oncoming vehicles, on motorists' visual attention. The average total fixation durations (ATFD), measured in seconds, within a prescribed AOI was used to measure motorists' visual attention on different targets. Findings related to motorists' visual attention include:

- The ATFDs on an adjacent bicyclist between the scenario where a bicyclist was approaching from behind and the scenario where a bicyclist was riding ahead of the motorist were statistically different (p-value <0.001). A statistically significant difference (p-value < 0.001) was also observed between the frequencies of motorist fixations on the bicyclist when the bicyclist was approaching from behind (44%) vs. when bicyclist was riding ahead (87%). Such scanning behavior places bicyclists approaching from behind in a more vulnerable situation where they are not detected by a motorist at an intersection, contributing to the occurrence of right-hook crashes.

- The ATFDs on the conflicting pedestrian (p-value = 0.039) and oncoming vehicles (p-value = 0.002), with respect to bicyclist's position, were statistically significant. This finding suggests that in the absence of the bicyclist in the focal vision, i.e. when the bicyclist was approaching from the behind, motorists spent more time fixating on other traffic elements immediately relevant to the safe operation of the vehicle.

- A statistically significant finding (p-value = 0.049) was observed in the ATFDs on the right-side mirror when the bicyclist was approaching from behind compared to when there was no bicyclist. This suggests that when a bicyclist approaching from behind was detected in the right side mirror, the motorist spent more time fixating on the right-side mirror while waiting for the bicyclist to pass at the intersection as compared to when there was no bicyclist present.

- Bicyclist's speed had a statistically significant effect on the ATFDs directed at the rear view mirror (p-value = 0.03), indicating that the total fixation duration on the rear view mirror in search of bicyclist was higher when the bicyclist traveled at a lower speed. This result is intuitive as the cyclist is visible in the mirror for a longer time at a lower speed.

- Statistically significant differences in the ATFDs were found for crossing pedestrians (p-value < 0.001), side traffic signal (p-value = 0.02) and bicyclist riding ahead of the motorist (p-value = 0.01) between all intersections with the presence of oncoming vehicular traffic vs. no oncoming vehicular traffic. Results suggest that in the presence of oncoming vehicular traffic, motorists spent the majority of their visual attention looking at the most significant hazards in their forward vision, i.e. oncoming left-turning traffic. These findings are consistent with previous findings of Hurwitz et al., Knodler and Noyce, and Summala et al. (*Hurwitz et al. 2013; Knodler and Noyce 2005; Summala et al. 1996*).

- The presence of a pedestrian had a statistically significant effect on the ATFDs of a bicyclist approaching from behind the motorist (p-value <0.001). Results suggest that when a conflicting pedestrian was in the motorists' focal vision, motorists spent more time fixating on the pedestrian and failed to fixate on the bicyclist that was approaching from behind in the blind spot.

T.4.2 Situational Awareness

Motorists' three levels of SA, i.e. Level 1 SA (perception), Level 2 SA (comprehension), Level 3 SA (projection) and the overall SA were measured immediately after six right-turning scenarios. The objective was to investigate if right-turning motorists were able to monitor adjacent traffic and use that knowledge to avoid collisions. SA findings are listed below.

*The relative position of an adjacent bicyclist significantly influenced right-turning motorists' overall SA (*p-value = 0.002) and Level 2 SA (p-value = 0.016). Participant's overall and Level 2 SA scores were lower when bicyclists were approaching from behind rather than riding ahead of the motorist. This finding reinforces the findings of Gugerty, Falzetta, and Crundall et al., who summarized that motorists focus the majority of their attention on nearby cars and cars in front of them that were perceived to most likely to pose a hazard and that they focused less attention on cars in the blind spot or in peripheral vision (*Gugerty 1997; Falzetta 2004; Crundall et al. 1999*). Also it demands greater working memory load to track an object in the blind spot (*Gugerty 1997*).

Motorists' Level 1 SA of the surrounding traffic significantly degraded when oncoming vehicles were present and the bicyclist was approaching from behind (p-value = 0.025). This observation could be explained by the cue utilization study, which evaluated the extent to which participants' behavior is constrained by environmental cues (*Brunswick 1956; Hursch et al. 1964*). In this experimental scenario, motorists' focal hazard-perception tasks competed for limited cognitive resources and eventually decreased the frequency of detecting peripheral visual events, i.e. the bicyclist approaching from behind led to poor Level 1 SA – a finding consistent with that of Crundall et al. (*Crundall et al. 1999*). However, motorists' projection (Level 3 SA) of the driving environment significantly degraded when the bicyclist was riding ahead of the motorist and oncoming vehicles were present (p-value < 0.001). This can be explained by the limitation of motorists' attentional capacity. With excessive demands on attention due to multiple environmental stimuli, (e.g., presence of a bicycle and oncoming cars), motorists' task performance declined as evidenced by reduced SA.

Since perception and detection of the hazard is an important criterion of crash avoidance, a Point biserial correlation analysis was conducted between participant's Level 1 SA score and crash occurrence, to determine the relationship between the two factors. A *significant negative linear association was found between the* Level 1 SA score *and crash occurrence (*r_{pbi}*= -0.3, p-value=0.043), indicating that* a *motorist with lower* Level 1 SA scores was more likely to be involved in a crash. *This finding suggests that a common cause of observed crashes was failure to detect the presence of an adjacent bicyclist before turning right during the latter portion of green phase at intersections.*

T.4.3 Crash Avoidance

The objective of considering this safety surrogate was to assess if motorists could avoid a crash with the adjacent bicyclist while performing a right-turn during the latter portion of the green phase. Motorist crash avoidance was measured as the number of motorists who could not avoid crashes with a through-moving bicyclist while turning right at 21 simulated signalized intersections. Findings related to crash avoidance are listed below.

Among 51 participants completing total of 1,071 right-turns, 23 participants could not avoid a crash with a bicyclist in 26 total right-hook crash scenarios. Relative position of a bicyclist, bicyclist speed, and the presence of an oncoming vehicle were found to have a statistically significant effect on crash occurrence. Twenty-four crashes occurred with the bicyclist approaching from behind in the motorists' blind spot and 21 of those crashes occurred in the presence of oncoming left-turning traffic. Additionally, in 23 observed crashes, bicyclists were approaching the intersection at higher speed, i.e. at 16 mph.

Male participants were involved in more right-hook crashes than female participants (p-value=0.02). Motorists' inadequate surveillance was found to be the major cause of observed right-hook crashes, in most cases (66%), the motorist did not check for the bicyclist in the mirror before turning and, in some cases (15%), they "looked but did not see" (inattention blindness). Some right-hook crashes (19%) were due to motorists' poor projection (the conflicting bicyclist was detected, but the motorist did not yield the right-of-way). This finding *suggests that a common cause of the observed crashes was due to the failure of detecting the adjacent bicyclist.* Near-crash events, where a collision between the right-turning motorist and through-moving bicyclist was imminent if their trajectories remained unchanged, were also investigated. The near-crash events were measured using a TTC upper threshold value of 1.5 seconds. Among 51 participants, who completed a total of 408 right-turns, 20 were involved in 26 severe near-crash events having TTC value less than or equal to 1.5 seconds. Inadequate surveillance was found to be the most common cause of near-crash incidents.

T.5.0 Field Validation

The research team reviewed 144 hours of video and identified 43 conflicts where the post encroachment time measured less than 5 seconds. The identification of conflicts that exactly matched the simulator was challenged by the relatively small numbers of observations per hour of collected field data, variable bicyclist speeds, and variable volumes of oncoming left-turning vehicular traffic. However, when field observations of scenarios most similar to those in the simulator were isolated, results indicated that the distribution of the PET/TTCs values observed in the simulator were consistent with those observed in the field. It can be concluded that the driving simulator scenarios, for which field data could be collected, modeled authentic driving conditions and that the driver interactions with adjacent bicyclists were representative of real world driver behaviors.

T.6.0 Effect of Design Treatments

The culminating experiment for this research was to study the effect of design treatments, (specifically signage, pavement markings, curb radii, and protected intersections), on the motorist behavior, using three different motorist performance measures: 1) visual attention of motorists, 2) their crash avoidance behavior, and 3) the potential severity of the near collisions or crashes, 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 under the highest driver loading scenario identified in Experiment 1. Additionally, follow-up survey responses were used to evaluate driver comprehension and driver preferences of specific treatments. This section summarizes the findings from each of the four design treatments of the second driving simulator experiment. These results are not found to be statistically significant, unless stated otherwise. However, the lack of a statistically significant effect for a particular treatment does not necessarily mean that the treatment will not have a positive effect on safety, rather that differences in the performance metric being analyzed were not statistically different in the data being analyzed. Finally, although we can measure the various driver performance metrics robustly, it is not yet clear how the magnitudes of the differences can be mapped to expected crash outcomes.

T.6.1 Signage Treatment

The findings of Experiment 2 indicate that the level one signage treatment, the ODOT OR10-15b "Turning Vehicles Yield to Bicycles" symbol sign, shown in Figure T.5, appeared to be an effective method of positively influencing driver behavior, with respect to visual attention.

Figure T.5: Experimental level one: ODOT OR10-15b "Turning Vehicles Yield to Bicycles"

The conclusions regarding this treatment can be summarized as follows:

- There is a generally positive pattern of change in visual attention with the addition of the sign (level one treatment). The level one signage treatment showed a 4% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero signage treatment. It specifically increased the amount of time spent scanning the side mirror for the bicyclist by 9% and the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 10%, in comparison to the level zero signage treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the sign (level one treatment). The level one signage treatment showed a 7% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero signage treatment. However, the level one signage treatment showed a 3% higher cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero signage treatment

- There is no consistent pattern of change in potential crash severity with the addition of the sign (level one treatment). The level one signage treatment showed a small 3% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero signage treatment. However, the level one signage treatment also showed a 35% larger range of vehicle velocities, in comparison to the level zero signage treatment.

T.6.2 Pavement Marking Treatment

The pavement marking treatments include four levels of treatment and a zero level of treatment, all shown in Figure T.6. The conclusions regarding these treatments can be summarized as follows:

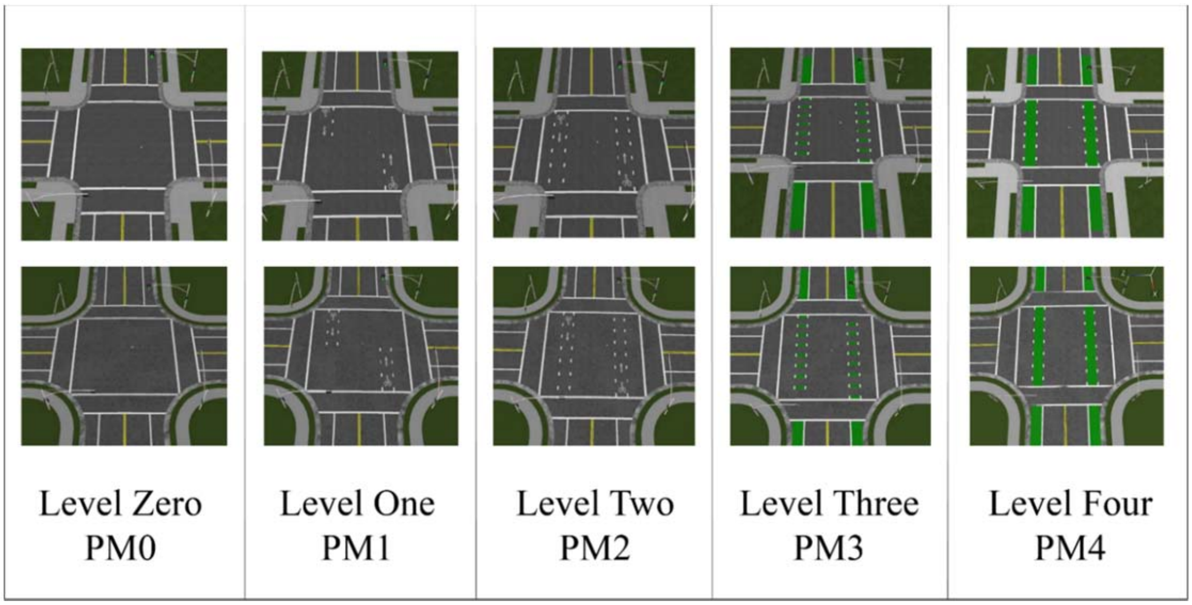


Figure T.6: Experimental levels of the pavement marking treatment

The findings of Experiment 2 indicate that the level one pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to crash avoidance.

- There is no consistent pattern of change in visual attention with the addition of the dotted white bike line with stencil, single line (level one treatment). The level one pavement marking treatment showed a 1% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment. It specifically increased the amount of time spent scanning the rear mirror by 13% and the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 13%, in comparison to the level zero pavement marking treatment. However, the presence of the level one pavement marking treatment also decreased the amount of time spent scanning the side mirror by 11% and the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 8%, in comparison to the level zero pavement marking treatment.

- There is a generally positive pattern of change in crash avoidance with the addition of the dotted white bike line with stencil, single line (level one treatment). The level one pavement marking treatment showed an 18% increase lower cumulative frequency of high risk TTCs, (equal to or less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Of the five pavement marking treatment levels, the presence of the level one pavement marking tied with the level three pavement marking treatment for the largest decrease in cumulative frequency of high-risk TTC values, in comparison to the level zero pavement marking treatment. Also, the level one pavement marking treatment showed a 15% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

- There is no consistent pattern of change in potential crash severity with the addition of the dotted white bike line with stencil, single line (level one treatment). The level one pavement marking treatment showed a 6% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. However, the level one pavement marking treatment also showed a 36% smaller range of vehicle velocities, in comparison to the level zero pavement marking treatment.

The findings of Experiment 2 indicate that the level two pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to visual attention.

- There is a generally positive pattern of change in visual attention with the addition of the dotted white bike line with stencil, double line (level two treatment). The presence of the level two pavement marking treatment showed a 10% increase in motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment (it is tied with the level four pavement marking treatment for the highest rate for all five pavement marking treatment levels). It also specifically increased the amount of time motorists' spent scanning the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 13%, in comparison to the level zero pavement marking treatment. However, the presence of the level two pavement marking treatment also decreased the amount of time motorists' spent scanning the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 6%, in comparison to the level zero pavement marking treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the dotted white bike line with stencil, double line (level two treatment). The level one pavement marking treatment showed a 12% higher cumulative frequency of high risk TTCs, (equal to or less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Of the five pavement marking treatment levels, the presence of the level two pavement marking treatment had the largest increase in cumulative frequency of high-risk TTC values. However, the level one pavement marking treatment showed a 4% lower cumulative frequency of high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

- There is a generally negative pattern of change in potential crash severity with the addition of the dotted white bike line with stencil, double line (level two treatment). The level two pavement marking treatment showed a 6% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. Additionally, the level two pavement marking treatment also showed a 14% larger range of vehicle velocities, in comparison to the level zero pavement marking treatment.

- It is important to note that the level two pavement marking treatment was the most preferred, according to the follow-up survey responses, with 50% of participants selecting it as their preferred pavement marking treatment.

The findings of Experiment 2 indicate that the level three pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to crash avoidance.

- There is no consistent pattern of change in visual attention with the addition of the skipped green bike lanes with white outline (level three treatment). The presence of the level three pavement marking treatment showed a 9% increase in motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment. It specifically increased the amount of time motorists' spent scanning the rear mirror by 10%, in comparison to the level zero pavement marking treatment. However, the presence of the level three pavement marking treatment also decreased the amount of time motorists' spent scanning the side mirror by 12% and the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 6%, in comparison to the level zero pavement marking treatment.

- There is a generally positive pattern of change in crash avoidance with the addition of the skipped green bike lanes with white outline (level three treatment). The presence of the level three pavement marking treatment had a statistically significant effect on the distribution of collisions and near-collisions, in comparison to the level zero pavement marking treatment (100% decrease in collisions and 18% decrease in near-collisions, with a p-value = 0.01). Also, the level three pavement marking treatment showed an 18% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero signage treatment. Of the five pavement marking treatment levels, the presence of the level three pavement marking tied with the level one pavement marking treatment for the largest decrease in cumulative frequency of high-risk TTC values, in comparison to the level zero pavement marking treatment. Also, the level three pavement marking showed a 2% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking.

- There is a generally negative pattern of change in potential crash severity with the addition of the skipped green bike lanes with white outline (level three treatment). The level three pavement marking treatment showed a 22% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. The level three pavement marking has the highest mean velocity of all pavement marking treatment levels. Additionally, the level three pavement marking treatment also showed a 1% larger range of vehicle velocities, in comparison to the level zero pavement marking treatment.

The findings of Experiment 2 indicate that the level four pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to crash avoidance and potential crash severity.

- There is a generally negative pattern of change in visual attention with the addition of the full green bike lanes with dotted white outline (level four treatment). The presence of the level four pavement marking treatment showed a 10% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment (it is tied with the level two pavement marking treatment for the highest rate for all five pavement marking treatment levels). However, the level four pavement marking treatment decreased the amount of time spent scanning the rearview and side mirrors in close proximity to the intersection (when the bicyclist is visible) by 12% and 22%, respectively, and the amount of time spent scanning the side mirror on the approach by 4%, in comparison to the level zero pavement marking treatment. The decrease in the amount of time spent scanning the side mirror in close proximity to the intersection was found to be statistically significant (p-value = 0.03).

- There is a generally positive pattern of change in crash avoidance with the addition of the full green bike lanes with dotted white outline (level four treatment). The level four pavement marking treatment showed a 13% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Also, the level four pavement marking treatment showed a 12% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

- There is a generally positive pattern of change in potential crash severity with the addition of the full green bike lanes with dotted white outline (level four treatment). The level three pavement marking treatment showed a 1% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. Additionally, the level four pavement marking treatment also showed a 38% smaller range of vehicle velocities, in comparison to the level zero pavement marking treatment.

- It is also important to note that when the survey responses for pavement marking treatment preference are broken down by gender, the level four pavement marking treatment was the most preferred by males, with 44% of male participants selecting it as their preferred pavement marking treatment.

T.6.3 Curb Radii Treatment

The findings of Experiment 2 indicate that the smaller, level one curb radii treatment, shown in Figure T.7, appears to be an effective method of positively influencing driver behavior, with respect to crash avoidance and potential crash severity. The level zero curb radii treatment has 30 ft. curb radii and the level one curb radii treatment has 10 ft. curb radii.

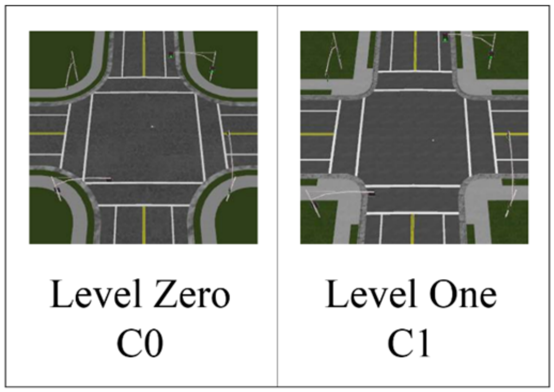


Figure T.7: Experimental levels of the curb radii treatment

The conclusions regarding these treatments can be summarized as follows:

- There is no consistent pattern of change in visual attention with the addition of the smaller curb radii (level one treatment). The presence of the smaller, level one curb radii treatment showed a 3% lower rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero curb radii treatment. The level one curb radii treatment decreased the amount of time spent scanning the side mirror by 15% and the rear mirror by 17%, in comparison to the level zero curb radii treatment. The decrease in the amount of time spent scanning the side mirror was found to be statistically significant (p-value = 0.04). However, the presence of the smaller, level one curb radii treatment increased the amount of time spent scanning the rearview mirror for the bicyclist in close proximity to the intersection (when the bicyclist is visible) by 14%, in comparison to the level zero curb radii treatment.

- There is a generally positive pattern of change in crash avoidance with the addition of the smaller curb radii (level one treatment). The level one curb radii treatment has the same cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero curb radii treatment. Additionally, the level one curb radii treatment showed a 7% lower cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero curb radii treatment.

- There is a generally positive pattern of change in potential crash severity with the addition of the smaller curb radii (level one treatment). The level one curb radii treatment showed a 4% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero curb radii treatment. Additionally, the level one curb radii treatment showed a 54% smaller range of vehicle velocities, in comparison to the level zero curb radii treatment. This finding of lower speeds for the smaller radii is a clear benefit and is consistent with the formulaic relationship between the design speed and the minimum radius of curvature, found in the AASHTO "A Policy on Geometric Design of Highways and Streets" *(AASHTO 2011).*

T.6.4 Protected Intersection Treatment

The protected intersection treatments include two levels of protected intersection treatment and a level zero of protected intersection treatment, all shown in Figure T.8. It should be noted that the protected intersection design used in the simulator was not intended to study constructability issues such as the truck turning/mountable curbs, reflective markings on curbs for visibility issues at night, and issues about downhill grades and accommodation of pedestrians.

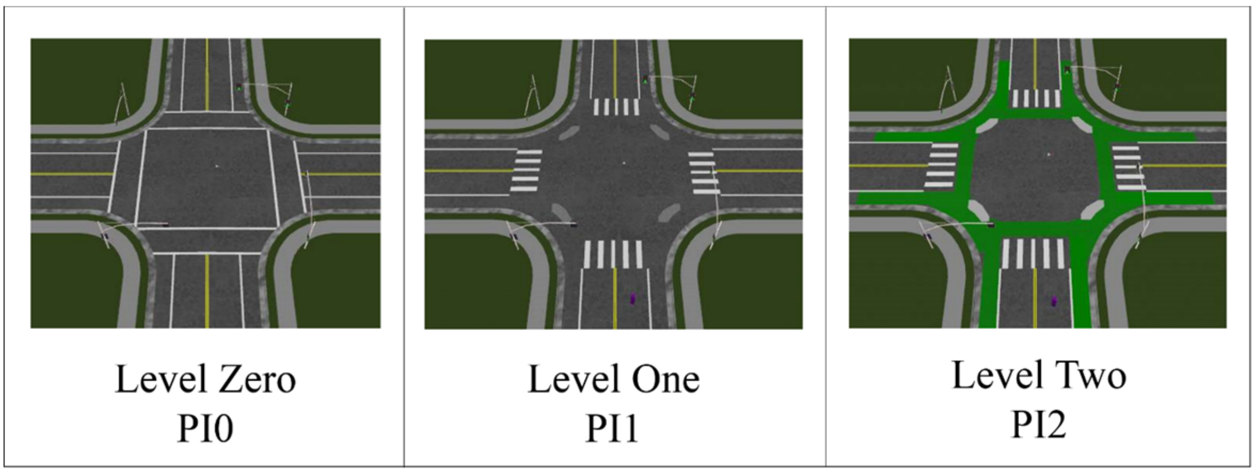


Figure T.8: Experimental levels of the protected intersection treatment

The conclusions regarding these treatments can be summarized as follows:

The findings of Experiment 2 indicate that the level one protected intersection treatments appears to be an effective method of positively influencing driver behavior with respect to potential crash severity.

- There is a generally negative pattern of change in visual attention with the addition of the protected intersection with islands (level one treatment). The presence of the level one protected intersection treatment showed a 3% lower rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero protected intersection treatment. It decreased the amount of time spend scanning the rear mirror by 19%, the side mirror by 24%, and the side mirror in close proximity to the intersection (when the bicyclist is visible in the side mirror) by 75%, in comparison to the level zero protected intersection treatment. However, it also increased the amount of time spent scanning the rear mirror for the bicyclist in close proximity to the intersection (when the bicyclist is visible in the rear mirror) by 7%, in comparison to the level zero protected intersection treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the protected intersection with islands (level one treatment). The level one protected intersection treatment showed a 19% lower cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero protected intersection treatment. Additionally, the level one protected intersection treatment showed a 5% higher cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero protected intersection treatment.

- There is a generally positive pattern of change in potential crash severity with the addition of the protected intersection with islands (level one treatment). The level one protected intersection treatment showed a 15% decrease in the mean velocity during moderate- to high-risk incidents, in comparison to the level zero protected intersection treatment. The impact of the level one protected intersection treatment on the range of vehicle velocities was unable to be calculated.

The findings of Experiment 2 indicate that the level two protected intersection treatment does not appear to be a consistently effective method of positively influencing driver behavior.

- There is no consistent pattern of change in visual attention with the addition of the protected intersection with islands and green pavement markings (level two treatment). The presence of the level two protected intersection treatment showed a 6% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero protected intersection treatment. It specifically increased the amount of time spent scanning the rear mirror for the bicyclist by 42%, in comparison to the level zero protected intersection treatment. However, it decreased the amount of time spent scanning the side mirror by 52%, and the rear and side mirror in close proximity to the intersection (when the bicyclist is visible in the mirror) by 55% and 25%, respectively, in comparison to the level zero protected intersection treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the protected intersection with islands and green pavement markings (level two treatment). The level two protected intersection treatment showed a 15% lower cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero protected intersection treatment. Additionally, the level two protected intersection treatment showed a 13% higher cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero protected intersection treatment. Also, the frequencies of both the moderate risk TTCs and high-risk TTCs were significantly lower than the level one protected intersection treatment (19 vs. 5 and 15 vs. 3, respectively).

- There is no consistent pattern of change in potential crash severity with the addition of the protected intersection with islands and green pavement markings (level two treatment). The level two protected intersection treatment showed a 10% decrease in the mean velocity during moderate- to high-risk incidents, in comparison to the level zero protected intersection treatment. However, the level two protected intersection treatment showed a 55% larger range of vehicle velocities, in comparison to the level zero protected intersection treatment.

- It is important to note that the level two protected intersection treatment out-performed the level one protected intersection treatment, with respect to the frequencies of driver comprehension of the correct vehicle path by 3%. The correct vehicle path is defined as the vehicle traveling around the island while executing the right turn and specifically not traveling on the bicyclist path located between the island and the curb.

T.7.0 Summary

This research produced a very consistent and coherent narrative about the right-hook crash. The research identified the intersection configuration with a bike lane to the right of a though motor vehicle lane as the most common profile. The research proceeds to identify the traffic situations that introduced the highest probabilities for driver errors. Then a carefully selected set of treatments were evaluated under these loading scenarios. The robust analysis of these driver performances measurable in the simulator was interpreted based on the positive outcome on various levels of driver performance as it relates to the safety of bicyclist.

Figure T.9 summarizes the results of Experiment 2 on the three metrics from the driving simulator and the one metric obtained from the survey. For clarification, the survey metric represents two different types of conclusions: for the pavement marking treatment, it represents the surveyed participant preference of the four pavement marking treatment levels, and for the protected intersection, it represents the measured driver comprehension of the correct vehicle path, (which is presented in Chapter 14, "Results: Experiment 2 Survey"). Blue checks indicate that the treatment had an improvement for the performance measure, the red Xs indicates that the treatment had a negative change for the performance measure, and the white dashes indicate no consistent pattern of improvement. It is notable that all treatments had some positive effect on measured driver performance. The sign, pavement markings and curb radius treatment groups are not mutually exclusive (i.e. the sign, a pavement marking, and smaller curb radius could be applied together).

Performance Measures	S1	PM1	PM2	PM3	PM4	C1	PI1	PI2
Visual Attention	✓	—	✓	—	✗	—	✗	—
Crash Avoidance	—	✓	—	✓	✓	✓	—	—
Potential Crash Severity	—	—	✗	✗	✓	✓	✓	—
Survey	n/a		✓ *			n/a	✗ **	✓ **

**This conclusion relates to the participants' selected preference of PM2 over the other three pavement marking treatment levels within the follow-up survey.*
***These conclusions relate to the measured driver comprehension of the correct vehicle path, which is presented in Chapter 14 "Results: Experiment 2 Survey.".*

Figure T.9: Summary of Experiment 2 treatment performance

In summary, the following observations and recommendations about each of the four treatment categories are:

- The presence of the sign improved driver performance across the visual attention spectrum. It appears the sign attracted driver's attentions and resulted in more searching for people on bicycles. Thus, given the relatively low cost of the sign, the "Turning Vehicles Yield to Bicycles" sign should be installed where feasible. To maximize the impacts, the sign should be installed in a location most visible to drivers and in advance of the turning-merge conflict area.

- The presence of through intersection markings also improved measured driver performance in the searching and crash avoidance spectrums. While all tested designs had some positive effects, the evidence from the simulator suggests that either the single, dotted white bike line with bicycle stencil pavement marking or the double, dotted white bike line with bicycle stencil pavement marking should be considered. The addition of green markings, commonly associated with bicycles, did not change the driver's visual attention measures as much as the simpler dotted line markings. The solid green marking, in fact, saw decreased visual attention performance.

- The use of a smaller curb radii produced decreases in vehicle turning speed and lower numbers of the high-risk conflicts. The reduction in vehicle turning speed was expected but is a clear measured benefit for safety.

- While the other treatments are easily implementable, the protected intersections with an island and/or green pavement marking would require further design work and consideration of many issues that were 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 corresponds to the curb radii treatments as the radii is larger for both treatments. The protected intersection design moves the conflict point between the car and bicycle forward in the intersection so it is different than the other treatments in that respect. Finally, unlike the other treatments, this was a novel design and not familiar to any driver.

E.8.0 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. While we can measure the various driver performance metrics robustly, it is not yet clear how to map the magnitudes of the differences to expected crash outcomes. Additional work is recommended to address the limitations of this study and to further consider the potential effects of the right-hook crash mitigation strategies from this research.

- One of the fundamental limitations of within-subject design is fatigue effects that can cause participant's performance to decline over time during the experiment. There is the possibility that participants might get tired or bored as the experiment progressed. Also, repeated right-turning maneuvers pose the threat of inducing simulator sickness more frequently than through movements in simulated driving. Therefore, to reduce the risk of fatigue effect and simulator sickness, the experiment could be conducted in two trials on two different days.

- Although many studies found an effect of driving experience on motorist's visual attention in driving simulator experiments *(Underwood et al. 2003; Pradhan et al. 2005),* this study did not find any significant difference on motorist's performance with respect to driving experience. A larger and more diverse sample may indicate some significance of driving experience on motorist's visual attention and crash avoidance.

- Additional variables could be included in the experiment to determine their effects on the occurrence of right-hook crashes, for example the conspicuity of bicyclist, and time of day. The assumption of constant speed of the approaching bicyclist is limiting; in reality some people on bicycles would slow down to avoid a collision or near collision.

- As noted, there are differences in Oregon driving code and practices with striping bicycle lanes all the way to the intersection that differs from practices in other states. Thus the use of drivers living in Oregon are likely to reflect the training and understanding of these designs that might differ from drivers elsewhere.

1.0 INTRODUCTION

With public interest seemingly increasing in sustainable transportation solutions—in part motivated by rising fuel prices and other concerns—bicycling has gradually become a more integral component of the multimodal transportation system in the U.S. As cities have made investments in the non-motorized transportation infrastructure, 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; SAFETEA-LU Section 1807 2012*). According to the National Personal Transportation Surveys (NPTS) of 1977 through 1995 and the National Household Travel Surveys (NHTS) of 2001 and 2009, the number of trips made by bicycle in the U.S. has more than tripled from 1977 to 2009 while the bike share of total trips almost doubled, rising from 0.6% to 1.0% (*NHTSA 2009; Pucher et al. 2011; FHWA 2010*). Bicycle sales in the U.S. have also increased from $15 million (projected) in 1973 to $6 billion in 2009 (*National Bicycle Dealers Association 2010*).

Clearly, increased levels of cycling has the potential to improve overall levels of public health, reduce emissions and improve parking, as well as enhance community livability by providing an alternative to driving and mitigate other transportation-related externalities (*FHWA 1994, 2010;U.S. Environmental Protection Agency 2012*). Since 50% of trips made by all modes in U.S. cities are shorter than three miles and 40% are shorter than two miles, there is tremendous potential for replacing those trips with bicycling. From the context of health benefits, studies found that adults who bike to work have healthier weight, blood pressure and insulin levels, and adolescents who bike are 48% less likely to be overweight as adults (*Menschik et al. 2008; Gordon-Larsen et al. 2009*). According to the Bureau of Transportation Statistics, the annual cost of owning and driving a car for an average American household is estimated to be $7,179 *(Bureau of Transportation Statistics 2010).* Compared to that, bicyclists save around $10 daily, or $3,650 annually, for a round-trip commute of 10 miles (*Bikes Belong 2013*). It has also been found that replacing one mile of driving with one mile of bicycling can prevent the production of nearly one pound of CO2 (0.88 lbs.) (*U.S. Environmental Protection Agency 2013*).

Still, much research has shown that safety is a primary concern for many people when considering transportation by bicycle. As shown in Table 1.1, the National Highway Traffic Safety Administration (NHTSA) reports that there were 677 fatal bicycle-related crashes in 2011, which accounted for 2% of transportation-related fatalities in the U.S. (*NHTSA 2011*). According to the NHTSA, "Crashes often occur at intersections because these are the locations where two or more roads cross each other and activities such as turning left, crossing over, and turning right have the potential for conflicts resulting in crashes," *(NHTSA 2010*). NHTSA reported that 69% of fatal crashes in the U.S. occurred in urban areas in 2011. Of all U.S. bicycle-involved fatal crashes, 33% occurred at intersections, 57% at non-intersections and 8% at other locations. In Oregon, 4,124 bicycle-motor vehicle crashes occurred from 2007-2010, and 66% of those crashes took place at intersections (*ODOT 2011*).

Table 1.1: Total fatalities and pedalcyclists fatalities, 2002-2011 *(NHTSA 2013)*

Year	Total Fatalities	Pedalcyclist Fatalities	Percent of Total Fatalities
2002	43,005	665	1.5
2003	42,884	629	1.5
2004	42,836	727	1.7
2005	43,510	786	1.8
2006	42,708	772	1.8
2007	41,259	701	1.7
2008	37,423	718	1.9
2009	33,883	628	1.9
2010	32,999	623	1.9
2011	32,367	677	2.1

1.1 MOTIVATION

Although intersections constitute only a small fraction of the overall area comprised by the surface transportation system, a comparatively large number of crashes occur at intersections since a variety of modes directly interact, sometimes in conflicting ways, at these locations. At intersections without space for both a separate right-turn and bicycle lane, bicyclists are often to the right of motorists as they approach an intersection. Though motorists must legally yield the right-of-way to bicyclists in bicycle lanes (in Oregon), motorists often fail to search for bicyclists, search but don't notice approaching bicyclists, or misjudge the gap of the approaching bicyclist. In addition, bicyclists do not always position themselves to be readily seen or approach at high rates of speed.

Bicycle-motor vehicle crashes involving right-turning vehicles and through-moving bicycles have been typed as "the right-hook." Right-hook crashes describe a type of bicycle-motor vehicle crash that occurs between a right-turning vehicle and a through-moving bicycle at an intersection. According to the Oregon Bicyclist Manual, "A right-hook occurs when a right-turning motorist crosses the path of a through bicyclist at an intersection" (*ODOT 2010b*). Right-hook crashes at intersections can occur as the result of several scenarios:

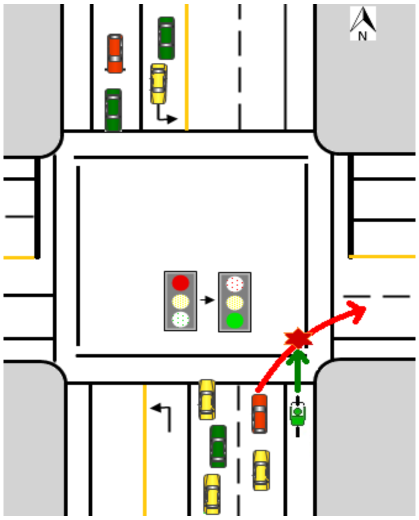
1. A right-hook at the onset of the green indication or at a stop sign can occur when a bicyclist stops to the right of a vehicle that is waiting at a red indication or STOP sign and fails to notice the bicyclist, who may be occluded in the vehicle's blind spot (Figure 1.1a and b). Immediately after the signal turns green, the bicyclist proceeds through the intersection and the motorist turns right, leading to a conflict and possible collision.

2. A right-hook can also occur at an intersection several seconds after the signal turns green when there is relative motion between the right-turning motorist and the through-moving bicyclist. Some literature has termed this a right-hook during the

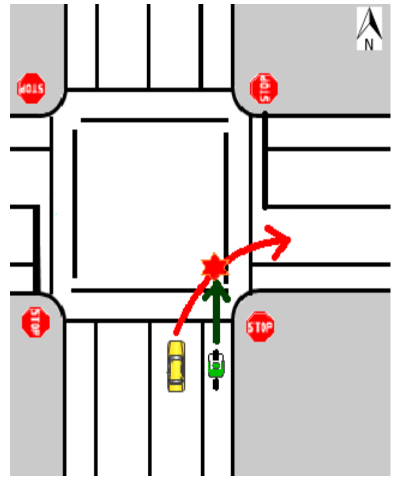
> "stale" green. This scenario where the light is green and the standing queue has been processed is also known as the "latter portion" of the green phase (sometimes called "stale green"). A right-hook crash in this condition can occur in two ways: a) when a bicyclist overtakes a slow-moving vehicle from the right and the vehicle unexpectedly makes a right turn (Figure 1.1c) or b) when a fast-moving vehicle overtakes the bicyclist and then tries to make a right turn directly in front of the bicyclist who is proceeding through the intersection (Figure 1.1d).

Oregon Revised Statute (ORS) 811.050 dictates that motor vehicles must yield to the bicycle rider in the bicycle lane, and that they may only enter or operate in the bicycle lane when "making a turn" as defined in ORS 811.440, though they still must yield to bicyclists. Thus, the legal provisions of the right-turning maneuver are clearly defined for Oregon drivers. This may differ from other states' practice. Also, Oregon practice continues the solid bicycle lane marking all the way to the intersection, which differs from the guidance in the Manual on Uniform Traffic Control Device's Figure 9C-6 which indicates a dotted line transition.

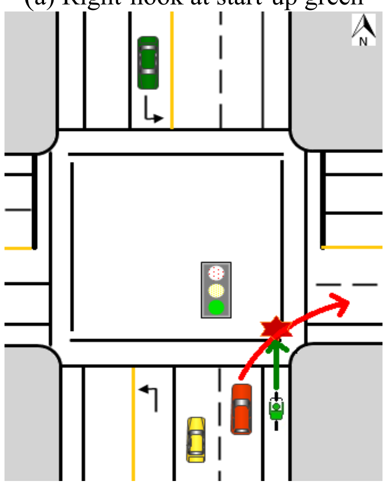
Although the incident of right-turning vehicle crashes with bicycles appears in the literature with some frequency (*Summala 1988; Weigand 2008*), little substantive research has been conducted on this topic.



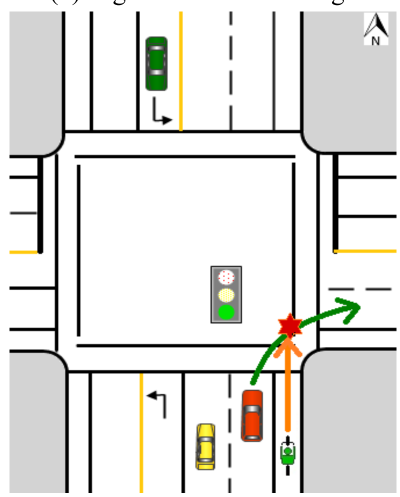
(a) Right-hook at start-up green



(b) Right-hook at STOP sign



(c) Cyclist passing slow-moving car



(d) Motorist passing cyclist

Figure 1.1: Potential right-hook crash schematics.

1.2 RESEARCH OBJECTIVES

The overall goal of the research was to quantify the safety performance of alternative traffic control strategies to mitigate right-turning vehicle-bicycle crashes at intersections in Oregon. Crash-based analysis of these design treatments are difficult, if not impossible, due to the low frequency of crashes and the variety of external factors that must be considered and controlled. The primary surrogate measures of safety—driver and cyclist behavior—are difficult to analyze in large quantities in consistent formats from passive video monitoring. This research leveraged the Oregon State University high-fidelity driving simulator to investigate the causal factors of right-hook crashes related to motorist behavior. The objectives can be described as follows:

1. To comprehensively analyze the literature and to develop an understanding of the known crash mechanisms;

2. To analyze Oregon crash records and to develop an understanding of the frequency of the crash problem at Oregon intersections and guide the design of the simulator experiment;

3. To address the identified gaps in the literature and develop a fundamentally better understanding of driver and bicyclist interactions during right-turning events at signalized intersections in a driving simulator;

4. To validate the driver performance and gap selection in the driving simulator with field observations; and

5. To evaluate potential design treatments through the observation of driver performance in a driving simulator.

1.3 ORGANIZATION OF THE REPORT

This report is organized as follows: This introductory chapter is followed by the literature review, which focuses on bicycle-involved crashes at intersections. A preliminary analysis of Oregon crash data follows in Chapter 3. In Chapter 4, the methodology employed that are common to both experiments, including the field validation setup and data processing, is described. Chapter 5 presents the detailed research designs for both Experiment 1 and Experiment 2. Chapter 6 summarizes the survey demographic data. Chapters 7-14 present the categories of results for the research. Finally, Chapter 15 presents the conclusions and summary of the work.

2.0 LITERATURE REVIEW

The review of the literature focuses on crashes at intersections. The first subsection reviews crash typing approaches that consider the characteristics of bicyclist-motorist interaction during crashes at intersections. The following sections examine the causes, both from the driver and bicyclist perspective, of bicycle-motor vehicle crashes at signalized intersections. The concept of situational awareness is then presented. The final section discusses measurement and types of traffic conflicts. The final section summarizes the literature review.

2.1 CRASH TYPOLOGIES

Crash typology or crash-typing system is an effective method to consider the behavior of bicyclists and motorists in different mixed-mode crash scenarios. According to NHTSA, "Crash-typing system is a method for assigning a crash to one of several categories based on common crash characteristics (*Karsch et al. 2012*)." It helps researchers to determine the relative frequencies of different types of crashes, and to analyze the scenarios and countermeasures for different crash types. It also helps to compare regional differences and trends over time for specific crash types.

The concept of pedestrian-motor vehicle crash typing was introduced in the early 1970s, and following that Cross and Fisher developed a similar crash typing for bicycle crashes (*Hunter et al. 1996 1997; Zeibots et al. 2012*). Cross and Fisher's typing was known as "problem types," where they categorized crashes into seven classes (A-G) that were subdivided into a total of 37 problem types (*Karsch et al. 2012; Cross and Fisher 1977*).

NHTSA adopted similar crash-typing methodology and developed the NHTSA Manual Accident Typing (MAT) for Bicyclist Accidents Coder's Handbook, which identified a total of 45 distinct bicycle-motor vehicle crash configurations (*Karsch et al. 2012; Hunter et al. 1995*). The initial classification step considers vehicle movements: parallel paths, crossing paths, and special circumstances. Each crash type is then characterized by a specific sequence of events, and each has precipitating actions; predisposing factors; and characteristic populations, locations, or both that can be targeted for interventions (*Hunter et al. 1996*). The *parallel path* crash describes the situation where a motor vehicle and bicycle approach each other on parallel paths, either heading in the same or opposite directions, whereas in a *crossing path* crash the bicycle and motor vehicle are oriented on intersecting paths. *Specific circumstance* crashes include the following four groups of events: non-roadway locations like parking lots, a motor vehicle that is backing, bicyclist riding a play vehicle such as a "big wheel" type tricycle, and "weird" crashes (for example, bicyclist struck by falling cargo).

To illustrate, one of the subgroups in the parallel path case was, "*motorist turn/merge into path of bicyclist.*" Four different kinds of events were included in this subgroup. These included motorist driving out from on-street parking (Code 35); motorist turning left in front of a bicyclist going in the same direction as the motorist (Code 22); motorist turning left in front of a bicyclist coming toward the motorist (Code 23); and motorist turning right and striking a bicyclist going either in the same or opposing direction (Code 24). Figure 2.1 shows each of the four different events that are included in the motorist turn/merge into the path of bicyclist subgroup (*Hunter et al. 1996*).

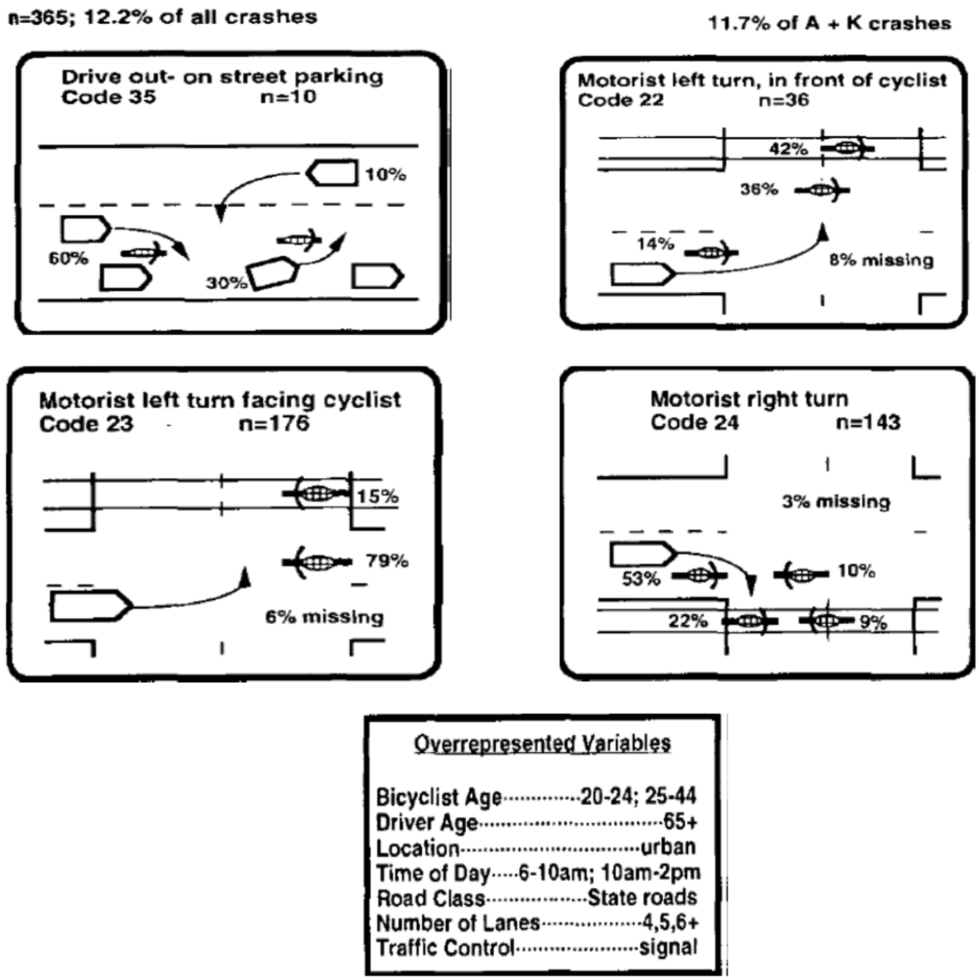


Figure 2.1: Crash typologies for parallel paths *(Hunter et al. 1996)*.

In order to illustrate this crash typing, 3,000 bicycle-motor vehicle (BMV) crash records collected from the states of California, Florida, Maryland, Minnesota, North Carolina, and Utah in the years of 1991 and 1992 were analyzed. Table 2.1 shows a summary of those crashes, and Table 2.2 shows the top 10 most frequent crash types.

Table 2.1: Summary of bicycle crash typing *(Hunter et al. 1996)*.

Crash Typing	Percent of total crashes
Crossing path crashes	58
Parallel path crashes	36
Specific circumstance crashes	6

Results also showed that the most common parallel path crashes were motorists turning or merging into a bicyclist's path (34.4% of all parallel path crashes). A common example of those parallel path crashes was when the motorist was making a right-turn and the bicyclist was riding in the same or opposite direction of traffic, which occurred in 143 cases (4.7%). However, in most of the cases (79% of those parallel path crashes), the bicyclist was riding the same direction as traffic. This crash (motorist right-turn) scenario is similar to the *right-hook crash* scenario. It was also found that immediately before those crashes the motorist was overtaking the bicyclist 74% of the time, the bicyclist was overtaking the motorist on the right 11% of the time, and the overtaking action was unknown in the remaining 15% of cases. The crash summary also determined that bicyclists from 20 to 24 and 25 to 44 years old were more likely to be involved in this crash type, which primarily took place on multilane roads (cross sections of four, five, six or more lanes). The regulatory speed limits of those roads ranged from between 31 mph to 37 mph. The crashes were 77% in urban areas and 23% in rural areas. It was reported that 11% of these crashes resulted in fatal or serious injuries. Bicyclists were riding in a bicycle lane only in 8% of these crashes (*Hunter et al. 1996*).

Table 2.2: Top 10 most frequent crash summary of crash typing *(Hunter et al. 1996)*.

Crash type description	n	Percent of Total	Percent of Crash Type, Fatal or Serious Injury
Ride out at stop sign	290	9.7%	23%
Drive out at stop sign	277	9.3%	10%
Ride out at intersection-other	211	7.1%	16%
Drive out at midblock	207	6.9%	7%
Motorist left turn-facing	176	5.9%	24%
Ride out at residential driveway	153	5.1%	24%
Motorist right-turn	143	4.7%	11%
Ride out at midblock	132	4.4%	20%
Bicyclist left turn in front of	130	4.3%	28%
Motorist overtaking-other	117	3.9%	28%

This early work by Hunter laid the foundation for the development of the Pedestrian and Bicycle Crash Analysis Tool (PBCAT) through the Highway Safety Research Center at the University of North Carolina sponsored by FHWA, in cooperation with NHTSA. *(Hunter 2006)* The PBCAT software was developed based on the NHTSA crash-typing scheme. It can be used by planners and engineers to develop and analyze a database containing the crash type and other details of crashes between motor vehicles and bicyclists or pedestrians (*Harkey et al. 1999; FHWA 2013)*. This software can also be used to assist transportation safety practitioners in selecting countermeasures to mitigate the crash problems identified.

The crash typing approach has been applied by others. In the study of 188 bicycle-motor vehicle crashes in four cities in Finland, Räsänen et al. developed a new crash-typing scheme for crashes in order to reconstruct the actual movements of those involved and to analyze the detection of the motorist or the bicyclist by one another (*Räsänen et al. 1998*). They aggregated crashes into four major categories, which were further organized into three or four subcategories. Table 2.3 and Figure 2.2 show the Räsänen and Summala crash-typing scheme. The most common crashes were categorized as Group II, where the motorist turned right and the bicyclist appeared from the right. This crash type—especially 1B1 and 1B2 in Figure 2.2—are similar to the right-hook crash type, with the exception that there is buffer space between bicyclists' travel path and the major road. Although these figures describe a European-centric design standard, they can be used to explain causes of the BMV crashes at intersections in the U.S. Räsänen et al. concluded that the misallocation of motorist attention resulting in failures to detect others and unjustified expectations about the behavior of others were the two major reasons behind this crash type (*Räsänen et al. 1998*). It was also found that sight obstacles could be a contributing factor to many crashes.

Table 2.3: Räsänen and Summala crash-typing scheme *(Karsch et al. 2012)*.

Group:	Definition:
I	Car turns, cycle path crosses street before road crossing – the bicycle may approach from the left or the right and the car may be turning either left or right (4 subtypes)
II	Car turns, cycle path crosses street after road crossing – the bicycle may be appearing from in front of or behind the car and the car may be turning left or right (4 subtypes)
III	Car drives straight ahead, cyclist comes from the left – the bicycle crossing is on the far side of a 3-way (T type) or 4-way intersection or the bicycle crossing is on the near side of a 3-way (T) intersection (3 subtypes)
IV	Car drives straight ahead, cyclist comes from the right – the bicycle crossing is on the far side of a 3-way (T) intersection, on the near side of a 3-way (T) intersection with one leg of the T going off to the right or to the left or the bicycle crossing is on the far side of a 4-way intersection

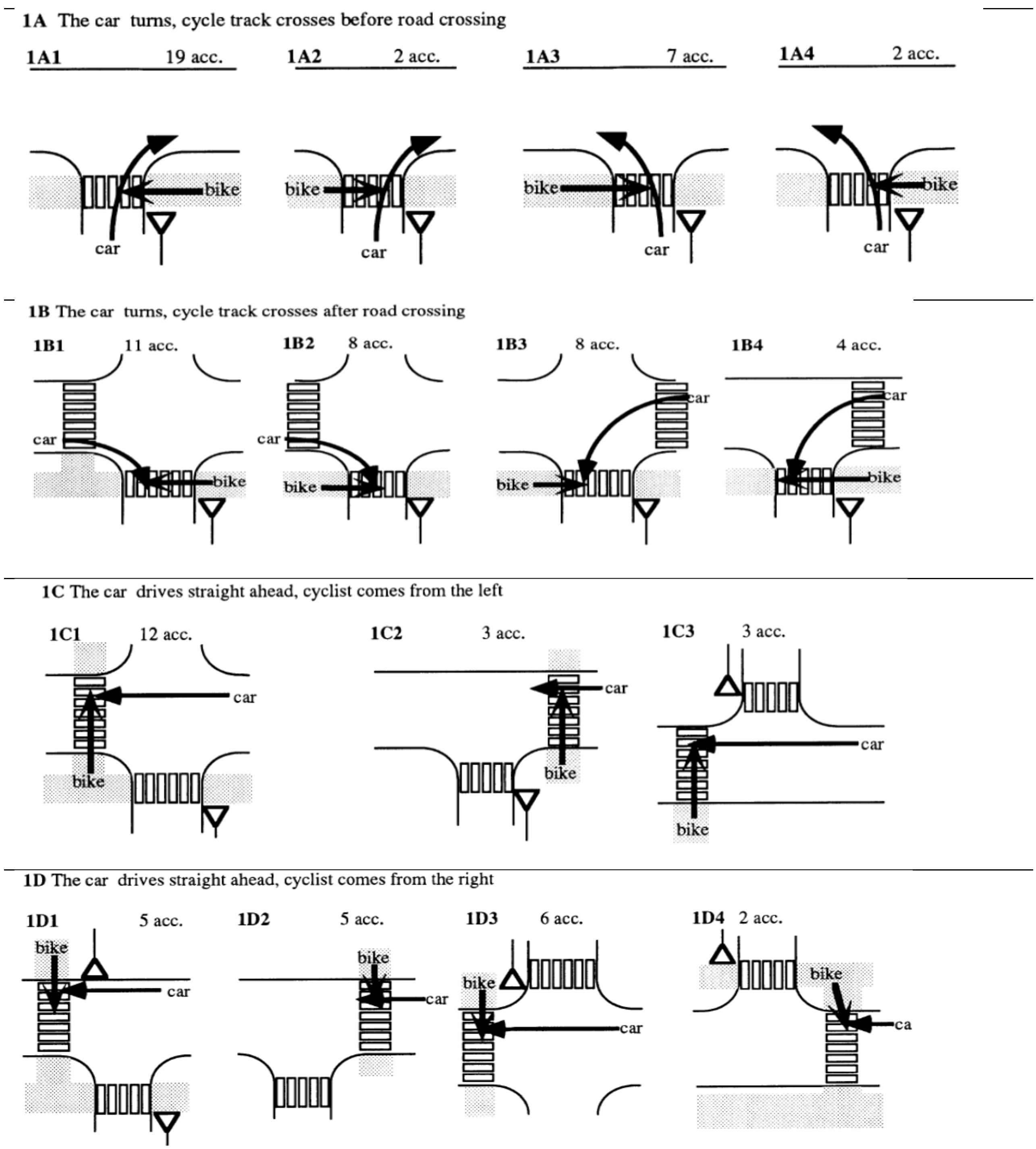
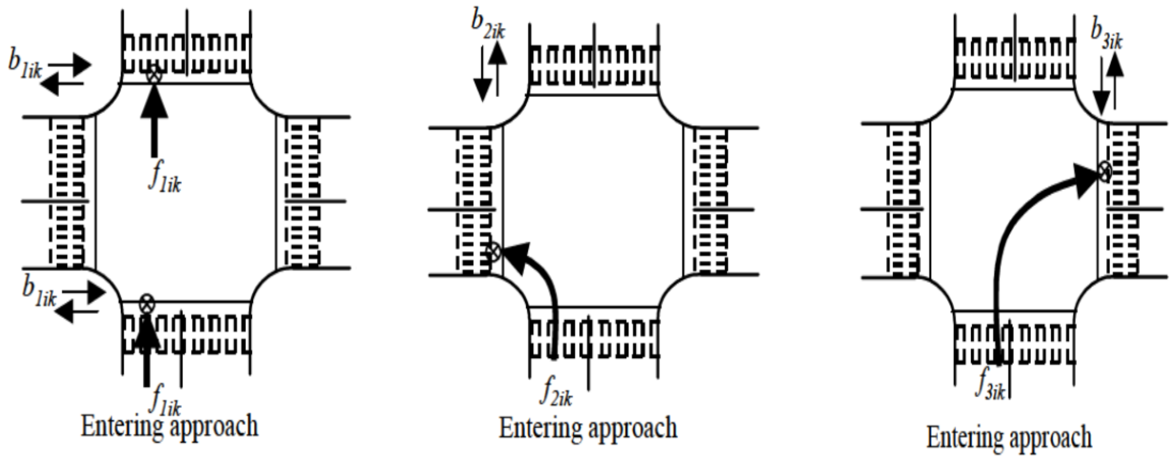


Figure 2.2: Räsänen and Summala crash-typing scheme, four intersections in 1B1 and 1B2 were signalized; two in 1B3; three in 1C1 and one in 1C2 *(Räsänen et al. 1998).*

To relate the risk of a specific BMV crash type to bicycle and motor vehicle volumes, Wang et al. classified crashes at four-legged signalized intersections into three groups: through motor vehicle, left-turning motor vehicle, and right-turning motor vehicle collisions, shown in Figure 2.3 (*Wang et al. 2004*). They abbreviated the phrase bicycle-motor vehicle as BMV and used four years of crash data collected from 115 randomly selected intersections in the Tokyo metropolitan area to estimate the expected accident risk of the three BMV crash types by the maximum likelihood method using a negative binomial probability formulation. The explanatory variables in the models included traffic and bicyclist volume, intersection location, visual noise, pedestrian overpasses, and median width.



(a) BMV Crash Type -1 (b) BMV Crash Type- 2 (c) BMV Crash Type - 3

Figure 2.3: Wang et al. crash-typing scheme *(Wang et al. 2004).*

2.2 CONTRIBUTING CRASH FACTORS

Vehicle collisions often result from the loss of control by one or more of the parties involved, and are often due to the loss of attention or a failure to detect the other party (*Korve and Niemeier 2002; Summala 1988; Summala et al. 1996; Räsänen et al. 1998; Rumar 1990*). The first most thorough investigation of the contributing factors for crashes was conducted in the 1970s by a research team from Indiana University for the NHTSA, known as the "Tri-Level Study of Accident Causes" (*Treat et al. 1979*). This study investigated 2,258 different types of police-reported crashes. Results from this study reported that improper lookout and inattention were the two leading direct human causes of those crashes. Improper lookout consisted both of "failed to look" and "looked but failed to see" *(Treat 1980).* In the first large-scale naturalistic study of 100 instrumented cars conducted by NHTSA in 2006, 241 motorists 18 years old and above were filmed inside their vehicles to study motorists' visual gazes from the video images of their face (*Klauer et al. 2006*). Detailed data were collected on vehicle, event, environment, motorist state (e.g., eye behavior, drowsiness) and narrative data on events in the data base: Crashes, near-crashes and incidents. Based on the analysis of motorists' behavior, this study reported that motorists' inattention contributed to 78% of the recorded crashes and 65% of the near-crashes. Neyens and Boyle analyzed the relationship among three types of crashes (angular, rear-end, fixed object) and four types of distractions (cognitive, cell phone, in vehicle, passenger-related) among young motorists (*Neyens and Boyle 2007*). Self-reported descriptions by motorists involved in crashes also confirmed attentional inefficiency expressed in the language "looked but failed to see" mainly was responsible for crashes (*Castro 2008*).

In a BMV crash, either the motorist or the bicyclist can be "at fault"; this section will review if the above mentioned motorist-related factors are responsible for vehicle crashes with bicyclists at an intersection. In the context of a bicycle-motor vehicle crash, Räsänen et al. stated that a motorist's learned routine may result in a failure to actively search for an adjacent bicyclist before turning, while bicyclists' expectations may be violated if they misinterpret motorists' behavior before crossing an intersection (*Räsänen et al. 1998*). This potential failure of user perceptions is a common feature characterizing right-hook crashes at intersections. In order to understand the right-hook crash scenario in better detail, this section reviews BMV-related crash factors by analyzing motorists' and bicyclists' perceptions during crashes.

2.2.1 **Factors Attributable to Motorist**

In a study of 39 BMV crashes, Summala et al. observed that one of the most frequent crash types was a motorist turning right and a bicyclist coming from the right (on the left side of the road) along a bike path (Figure 2.4), which accounted for 70% of the observed crashes (*Summala et al. 1996*). The authors determined that one of the contributing factors of this crash type is the improper allocation of a motorist's visual attention while making turns at an intersection, which is similar to the "improper lookout" cause found in the crash study of "Tri-Level Study of Accident Causes" (*Treat et al. 1979*). In this study, Summala et al. found that before making a right-turn, motorists focus their visual attention on the cars coming from the left, and fail to detect the bicyclist coming from their right early enough to respond safely (*Summala et al. 1996*).

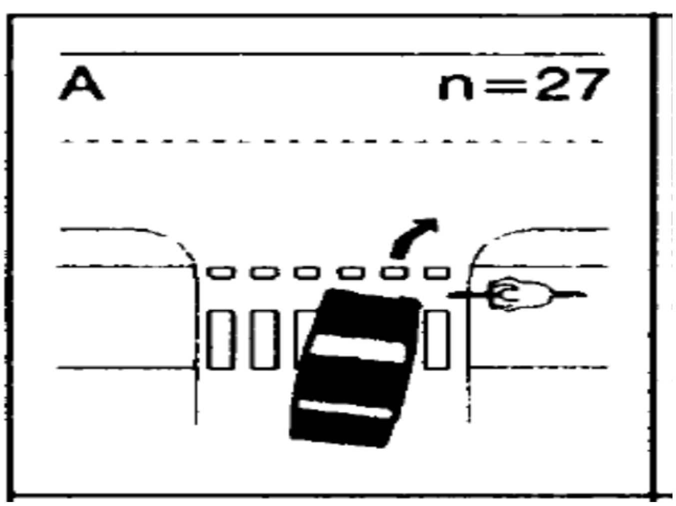


Figure 2.4: Vehicle turning right at intersection *(Summala et al. 1996).*

Räsänen et al. studied 188 police-reported BMV crashes from four major cities in Finland (*Räsänen et al. 1998*). In this study, estimates about parties' behavior were based on structured interviews made by a police officer after the crash. Based on their analysis, the authors confirmed that attention misallocation among motorists may lead to a situation where they may not notice a bicyclist coming from an unexpected direction. Even if motorists look in the relevant direction and notice the bicyclist, often times the identification is too late to effectively stop or yield. This study concluded that only 11% of the motorists noticed the bicyclist before impact and in 37% of the crashes, neither motorist nor bicyclist realized the hazard or had time to yield. Wachtel et al. found a similar trend in a study of 371 police-reported bicycle-motor vehicle crashes in Palo Alto, CA (*Wachtel et al. 1994*). Analyzing the crash data by bicyclists' age, sex, direction of travel and position on the road, the authors concluded that motorists turning right at an intersection scanned to the left for approaching traffic on the new road, and failed to detect or anticipate a fast-moving, wrong-way bicyclist approaching from the right, which is one of the most common types of BMV crash in Palo Alto. The Wachtel study included many sidewalk-riding crashes, which are known to be an elevated risk scenario for bicyclists. This crash scenario is similar to one of the crash scenarios described by Räsänen et al., where motorists turning right focus their attention on the cars coming from the left and fail to detect the bicyclist coming from their right, as depicted in Figure 3.2 (*Räsänen et al. 1998*).

NHTSA conducted a study to examine the general characteristics of motor-vehicle traffic crashes at intersections using the National Motor Vehicle Crash Causation Survey (NMVCCS) from 2005 to 2007 (*NHTSA 2010*). The NMVCCS data is a nationally representative sample of crashes that occurred between 6 a.m. and midnight that contains on-scene information on the events and associated factors leading up to a crash. Among those records, there were 756,570 intersection-related crashes; 55.7% of the crashes occurred due to motorists' recognition error, such as inattention, internal and external distractions, inadequate surveillance, etc.; and 29.2% of crashes were due to decision errors, such as driving too fast for conditions or aggressive driving, false assumption of other's actions, illegal maneuver, and misjudgment of gap or other's speed. The most frequently assigned critical reason was found to be inadequate surveillance, which constituted 44.1% of total intersection-related crashes. Inadequate surveillance occurs when the motorist is in a situation where he needs to scan a certain location to safely complete a maneuver and either fails to look in the appropriate place or looks, but does not see. This failure can occur at an intersection when the motorist looks at the required direction before making a turn, but fails to see the approaching traffic (*Dingus et al. 2006*).

The NHTSA study also attempted to identify patterns of motorist-attributed characteristics for intersection-related crashes, such as a motorist's age and sex (*NHTSA 2010*). Aggregating the crashes according to a motorist's age group, it was determined that 33% of crashes involving a motorist 20 years old or younger were intersection-related. However, among all crashes where motorists were 65 and older, 53.9% were intersection-related. Overall, it was found that the proportion of intersection-related crashes showed an increasing trend as the age of motorists involved increased. It was postulated that the contributing factors for crashes at signalized intersection involving motorists 24 years old and younger were "internal distraction," "false assumption of other's action," "too fast for conditions or aggressive driving," or "external distraction." In contrast, the contributing factors for crashes involving motorists 25 to 54 years old were "critical non-performance error," "illegal maneuver," "inattention," and "too fast for conditions or aggressive driving." Additionally, for crashes at stop-controlled intersections involving motorists 55 and older, the contributing factors included "inadequate surveillance" and "misjudgment of gap or other's speed," while for motorists 24 years old and younger the primary contributing factor was "turned with obstructed view" (*NHTSA 2010*).

While analyzing intersection-related crashes according to gender, the study found that of all the crashes involving female motorists, 41.1% occurred at intersections while only 32.2 % of crashes involving male motorists were intersection-related. The study stated that male motorists of all ages were likely to be involved in intersection-related crashes due to "illegal maneuvers," "aggressive driving," or "driving too fast for conditions." Again, for both male and female motorists 55 and older, crash factors were found to be "misjudgment of gap or other's speed" and "inadequate surveillance." For female motorists involved in intersection-related crashes, the contributing factors included "internal distraction" or "inattention," whereas those were "illegal maneuver," "false assumption of other's action," and "too fast for conditions or aggressive driving" for male motorists. Of particular interest for right-hook crashes, the study found that male motorists were much more likely to have a false assumption of other's action as a contributing factor in crashes (*NHTSA 2010*).

2.2.2 Factors Attributable to Bicyclists

In a study of bicycle crashes at intersections, the Institute of Transportation and Traffic Engineering (ITTE) at the University of California, LA concluded that in the vicinity of intersections, bicyclists are often involved in crashes because they cannot clearly perceive dangers (*Chao et al. 1978*). Bicyclists assumed that the motorist would give way as required by the law. This becomes more severe when bicyclists ride on familiar routes. The combination studies have assumed that bicyclists who make a left turn are exposed to the greatest danger (*Summala et al. 1996; Räsänen and Summala 1998*), bicyclists turning right or travelling straight are also exposed to risk. As explained in those studies, bicyclists may be less vigilant in searching for hazards as they perceive the right side of the road to be safer due to fewer potential conflicts (but this is just speculation). Räsänen and Summala determined that one of the contributing factors to BMV crashes at intersections was bicyclists' misplaced attention on a familiar route (i.e., not focusing attention in the appropriate direction) and the assumption of right-of-way may result in a situation where bicyclists do not actively search for motor vehicles coming from their left, contributing to right-hook crashes (*Räsänen and Summala 1998*).

Karsch et al. reviewed the pedestrian and bicyclist safety research literature from 1991 to 2007, which stated that for all the BMV crashes in 2009 the most common bicyclist contributing factors were failure to yield to motorists (21%), and riding against traffic (15%). Stop sign violations and safe movement violations represented another 7.8% and 6.1%, respectively (*Karsch et al. 2012*).

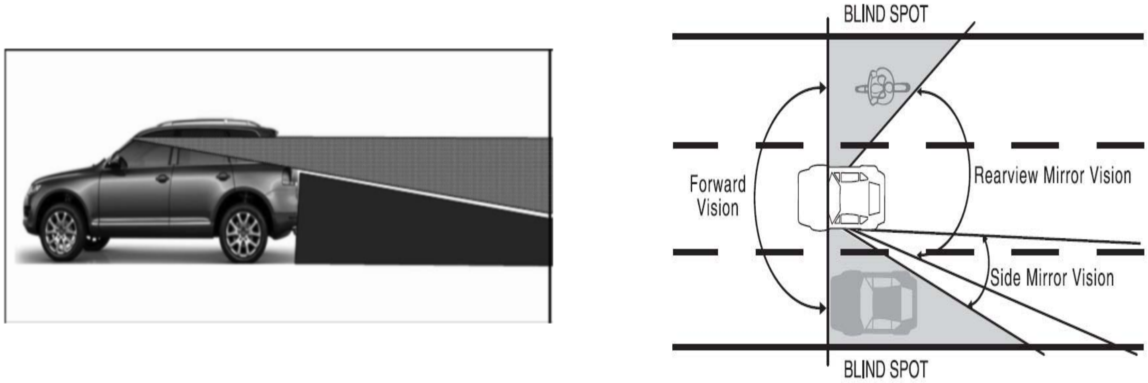
NHTSA data showed that in 2010, 534 male bicyclists were killed, resulting in a fatality rate of 3.51 fatalities per million people (*NHTSA 2011*). In contrast, there were 84 female bicyclist fatalities, resulting in a fatality rate of 0.53 per million people, seven times lower than men. The highest number of male bicyclist fatalities was for bicyclists between the ages of 45 and 54. This result suggested that the overrepresentation of male bicyclists in injuries and fatalities may be due to riding in more dangerous situations or engaging in riskier riding behaviors than females, respectively (*Karsch et al. 2012*).

However, per capita rates as a measure of exposure can be misleading since it fails to account for the fact that the observed cycling gender splits do not mirror the population (in the U.S. and Canada cyclists are male (typically 70% male) though in bicycle-friendly areas of cities like Portland, OR and Davis, CA can be more representative of the population *(Pucher and Buehler, 2012).* In a study by Li et al. analyzing data from the National Center for Health Statistics (NCHS), the National Electronic Injury Surveillance System (NEISS) and the NPTS reported that male bicyclists were overrepresented in bicycling fatalities due to their higher number of trips by bicycle (*Li et al. 2000*). Furthermore, the study revealed that when involved in a crash, male bicyclists tended to sustain more severe injuries than female bicyclists (*Karsch et al. 2012*). However, when analyzing the data on a per trip basis, men were found to be at a slightly lower injury risk than women (*Li and Baker 1996*).

Studies showed that bicyclists on a sidewalk or bicycle path were 1.8 times more likely to get involved in an intersection crash than those riding on the road, most probably due to blind-spot conflicts at intersections (*Karsch et al. 2012*). Blind-spot conflicts occur when a bicyclist is located in the blind point of a vehicle (i.e., the areas on the road that cannot be seen in the mirrors on either or both sides of the vehicle) (Figure 2.5). Paine and Henderson stated that even when the entire field of view is available to the motorist, such as when the rear window, the interior rearview mirror and the external rearview mirrors are used in combination, there are still blind spots behind the vehicle (*Paine and Henderson 2011*). The extent of these blind spots depends on the characteristics of the vehicle, together with the size of the motorist (mainly eye height when seated) and the height of the object to be detected. Based on the research on blind spots of different vehicle types, it was found that 1.97-foot object was not visible any closer than 15 to 30 feet from the rear of most station wagons and SUVs (*Paine and Henderson 2001*). Measuring the blind spots of different vehicle types, Consumer Reports mentioned that the average blind spot of a sedan ranged from 10 to 35 feet, whereas for SUVs and pickups, the average blind spot was up to 50 feet (*Consumer Reports 2005*). Due to the size and height, trucks or buses have four blind spots or “no-zones” (Figure 2.6). No-zones are actual blind spots where vehicles “disappear” or become invisible from the view of the truck or bus driver *(NCDOT 2007).* As stated by the American Automobile Association (AAA), the front no-zone extends to 10 to 20 feet in front of the truck cab and the rear no-zone extends to 200 feet behind a truck, which is compared to two-thirds the length of a football field (*AAA 2011*). Regarding side no-zones, trucks have extremely large blind spots on both sides, even with large side-view mirror - much larger than the blind spots motorist experience while driving a car *(AAA 2011).* Therefore, for side no-zones the message is don’t “hang out” on either side of trucks, or if very necessary to pass it is recommended to allow plenty of space and extra time while passing a truck (*AAA 2011; UDOT 2013*).

The probability of bicyclists on sidewalks to be obscured by parked cars, buildings, fences, and shrubbery is more likely than bicyclists on the road. Due to the likelihood of blind-spot conflicts, this obscured bicyclist poses greater risk for a right-turning vehicle at an intersection since their required stopping distance is much longer than a pedestrian’s and they have less maneuverability (*Wachtel et al. 1994*). Several studies have been conducted to evaluate mitigation strategies to prevent run-over backing crashes with objects or young children obscured in a vehicle’s blind spots (*Hurwitz et al. 2009; Muttart et al. 2011; Paine and Henderson 2011*). With the aim to reduce backing crashes, Hurwitz et al. evaluated whether the integration of rear-view cameras with an audible warning system can reduce backing-crash rates

(*Hurwitz et al. 2009*). Muttart et al. proposed a backing warning system based upon motorists' response times and backing acceleration in different scenarios (*Muttart et al. 2011*). Paine and Henderson evaluated possible technical solutions, including proximity sensors and visual aids, to reduce the risk of backing-crash injuries for young children (*Paine and Henderson 2011*). Their evaluation involved determining blind spots at the rear of the vehicle through 'Blind Spot' tests, and evaluating whether visual aids and/or sensor systems can effectively cover these blind spots.



a) The cone of visibility (lighter shaded region) and obscured (darker shaded region) areas behind a high profile vehicle (Muttart et al. 2011)

b) blind spot of passenger vehicle

Figure 2.5: Typical areas of a driver's blind spot.

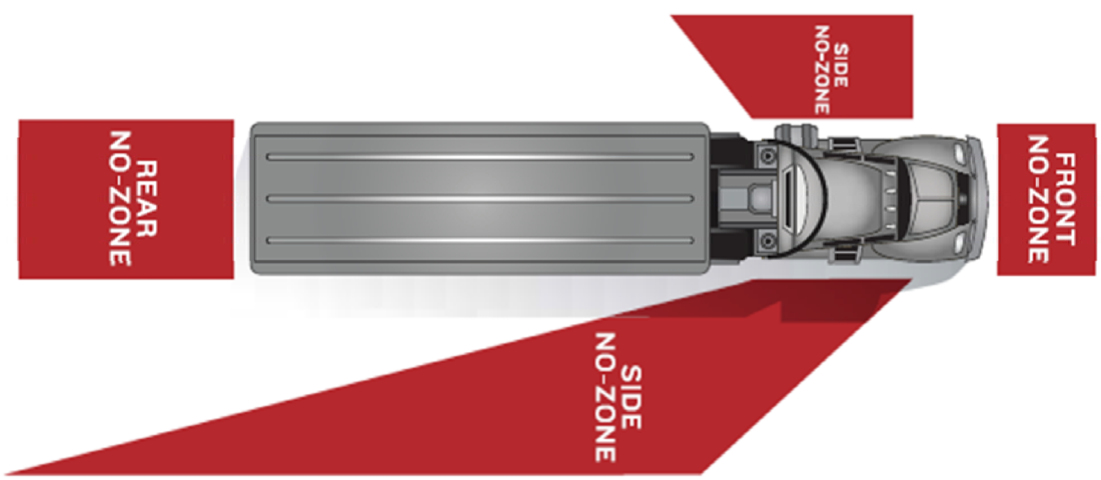


Figure 2.6: Blind spot or "no-zones" of truck *(AAA 2011).*

2.3 MEASURING MOTORISTS' DRIVING PERFORMANCE

In support of measuring driver performance in a driving simulator, this section reviews some of the critical research. Given the clear contribution of motorist attention in crash causations, empirical measures are needed.

2.3.1 **Acquisition of Visual Information**

Gibson et al. stated that, "of all the abilities that contemporary civilization requires of us, driving is the most important for individuals in the sense that errors in this ability translate into the greatest threat to human life" (*Gibson and Crooks 1938*). This statement indicates the importance of safe driving, and the correlation between errors in motorist performance and safety. Shinar described driving as an information-processing task in which most of the information is received through the visual channel (*Shinar 2007*).

While driving can be considered an information-processing task, the most critical component of the information-processing model is attention (*Klauer et al. 2006*). Addressing the motorist as an active information processor, Castro presented the following statistics to underline the importance of motorists' perception and attention during driving: 1) more than 90% of traffic crashes are due to human error (*Fell 1976; Castro 2008*); 2) more than 90% of those are due to problems with visual information acquisition (*Hills 1980; Olson 1993*); and 3) the majority of motorists reported that the causes of crashes were "I looked, but I didn't see it" (i.e., inattention blindness type) (*Castro 2008*).

Numerous studies agree that inattention and distraction are major contributing factors for motor vehicle-related crashes (*Fisher et al. 2011*). To identify the role of inattention and distraction in the causes of crashes, early studies often used estimates from police crash reports (*Sabey and Staughton 1975; Treat, et al. 1979; Fisher et al. 2011*). However, with the change in the technology regarding information acquisition over the last five years, eye behaviors are contributing significantly to identify the cause of crashes due to distraction and inattention (*Fisher et al. 2011*). Therefore, information regarding motorists' eye movement and visual attention, in particular information on where the motorist was looking and for how long immediately before a crash occurred, can explain whether it was the motorist or the environment that the motorist was exposed to that was likely responsible for the crash (*Fisher et al. 2011*).

Motorists' eye movements and visual attention can be directly related to crash causality. For example, motorists may fail to anticipate hazards or fail to scan locations on roadways that may contain threats which could materialize suddenly, which can lead to crashes (*Fisher et al. 2011*). As reported by McKnight and McKnight, the majority of crashes are caused by failures to scan the roadway adequately (*McKnight and McKnight 2003*). Crashes may also occur when a motorist fails to perceive or identify a threat on the road in spite of directly looking at that threat. In the psychological literature, this is termed as *inattention blindness* which is the failure to notice something when the observer directly looks at it (*Mack and Rock 1998; Simons and Chabris 1999*). Cognitive distraction is a common cause of inattention blindness. According to NHTSA, cognitive distraction is defined as the mental workload associated with a task that involves thinking about something other than the driving task (*NHTSA 2010a*).

2.3.1.1 Measuring Eye Movement

The Society of Automotive Engineers (SAE) and the International Standards Organization (ISO) publications have defined standardized terms for eye movement in automotive contexts *(SAE 2000; ISO 2002*). One category of eye movements is fixation, which occurs when the gaze is directed towards a particular location and remains still for some period of time, typically around 0.20-0.35 seconds (*Green 2007; Fisher et al. 2011*). Fixations are separated by rapid eye movements called saccades. Although sometimes saccades (movements within regions) and transitions (movements between regions) are used synonymously, the SAE Recommended Practice (12396) recommends distinguishing them (*Green 2007*). Again, some literature used the terms “fixation” and “glance” synonymously, whereas a glance consists of all consecutive fixations on a target plus the preceding transitions. Figure 2.7 is a “Transition Diagram” that distinguishes the eye-movement terms described above.

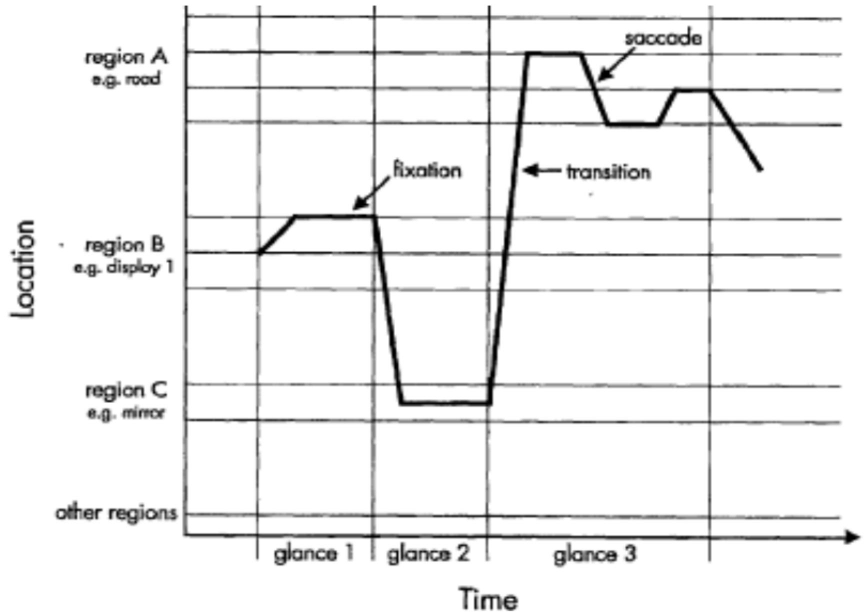


Figure 2.7: Transition diagram (Green 2007).

Very little new information is obtained during saccades and transitions due to the phenomenon known as saccadic suppression (*Matin 1982*). People are unaware of the blurry moving image on the retina during the saccade, mostly due to the reason that it is backwardly masked by the visual information from the fixation following the saccade. Therefore, the fixation is of primary measure of interest. It is very unlikely that objects not fixated will be encoded, and longer times fixating on an object indicate difficulty processing an object. Therefore, the duration and location of fixations both indicate that an object that is being fixated on is being processed (*Fisher et al. 2011*). While fixation and saccades are measures of eye movement for static images, smooth pursuit movements are measures of eye movement when the object is moving with respect to the observer, such as a pedestrian, or when the observer is moving, such as reading a speed limit sign during driving (*Fisher et al. 2011*).

Fisher et al. have also classified the measures of eye movement according to spatial and temporal characteristics (*Fisher et al. 2011*). Spatial parameters of eye movement provide information on whether an object or area in the scene has been processed, such as a fixation or gaze location. Spatial parameters are of particular interest to determine novice and older motorists’ behavior, given their optimal fixation pattern is known (*Fisher et al. 2011*). The sequence of fixations is another important spatial parameter with respect to eye movement, and the concept of areas of interest (AOIs) is of particular interest in this regard. Since driving is a dynamic task, motorists must monitor a series of dynamic processes at known locations, such as gauges, roadways, and traffic signals - each mapping onto a respective AOI defined by the scenario. The proportion of glances on each AOI is then measured and compared across group or conditions to gain information on when and where motorists looked *(Maltz and Shinar 1999).* In addition, the scan path of motorists can also be measured, which is defined by the sequence of gazes in different locations or different AOIs. Temporal parameters of eye movements provide useful information on the duration of fixations and glance duration, which can be a useful measure in this regard (*Fisher et al. 2011*).

Many researchers have studied motorists' eye movement in order to determine how likely a motorist is to crash (*Scholl et al. 2003*), and how differences in eye behavior appear to be related to crash rates (*Mourant and Rockwell1972; Underwood et al. 2003; Pollatsek et al. 2006*). Studying the anticipatory glances to areas of the roadways where potential threats might appear, Pradhan et al. found that novice motorists can be around six times less likely to glance at potential threat areas (*Pradhan et al. 2005*). Again, based on previous experimentation, the mean glance duration is typically 10 to 50 milliseconds shorter for experienced motorists than novice motorists (*Laya 1992; Crundall et al. 1998*). Other than experience being a probable reason for this difference, Fisher et al. hypothesized that novice motorists simply fail to recognize the need to scan for the potential threat on roadways *(Fisher et al. 2011).* An alternative hypothesis proposed by the author was that novice motorists are overloaded with the demands of driving and therefore do not have the spare capacity left to make the prediction they need to launch the anticipatory eye movement. Using an eye tracker and a driving simulator, Garay-Vega et al. conducted experiments to evaluate these two hypotheses (*Garay-Vega et al. 2007*). Findings from those experiments showed that although load appeared to contribute somewhat to the depressed anticipatory glances for novice motorists, the difference mostly occurred because novice motorists were not aware of the necessity of making such eye movements. Thus it was determined that without knowledge of eye behavior, it would not have been possible to test those hypotheses or produce results. Studies also found that experienced motorists look at their mirrors more than novices and look farther down the road than novices, who tend to focus close to the front of the vehicle (*Chapman and Underwood 1998; Mourant and Rockwell 1972*).Therefore, knowledge of eye behavior is critical to gain real insights on the causes of crashes and also how the design of the interface with the motorist, such as signs, music retrieval systems and so on, can be improved to minimize crash risk.

2.3.1.2 Techniques

Using an early model eye-movement camera, Rockwell et al. developed the first eye-tracking system that monitored and recorded motorists' on-road visual scanning behavior *(Rockwell et al. 1968).* In recent days, motorists' eye behavior can be measured either in a driving simulator or on the road in an instrumented car (*Chrysler et al. 2004*) either directly from the recording of a camera aimed at a motorist's face known as the direct observation method, or by using special electronic devices often referred to as "gaze trackers" or "eye movement recorders" (*Green 1992; Williams and Hoekstra 1994*).

Direct observations are labor intensive and time consuming to process; the video tapes must be played back frame by frame, so often only a small fraction of the data collected is analyzed (*Green 2007*). For standard video equipment (operating at 30 frames per second), times are accurate to the nearest 33 milliseconds. Electronic devices typically record (1) the reflection of a beam of light off of the cornea; (2) the electrical signals of the muscles controlling the eye, or; (3) the location of the boundary between the white and dark parts of the eye. None of these methods are ideal and each technology has limitations (use in daylight, vertical accuracy, wearer discomfort, and so on) for particular conditions. Currently, the most widely used technology for in-vehicle studies (off-head cameras that track the eyes) utilizes the white/dark boundary of the eyes. Further, glasses or contacts may interfere with measurements, a consideration of special relevance to older motorists, almost all of whom wear corrective eye wear.

Eye movement data collected with eye-tracker technology provides direct evidence about whether potential hazards were being anticipated in most cases (*Fisher et al. 2011*). Eye trackers can also provide reliable information about motorists' eye movement during instances when motorists look but fail to identify threats or inattention blindness if a crash occurs. But in the absence of a crash, it is difficult to definitely determine if a motorist is looking but not seeing exclusively with an eye tracker (*Fisher et al. 2011*). However, as argued by Fisher et al., an increase in inattention blindness will increase the likelihood of crashes. Therefore, information on the occurrence of inattention blindness in the more general driving environment collected by eye trackers can be very useful in this regard. Strayer et al. used an eye tracker and driving simulator to assess whether cell-phone conversation affects motorists' driving performance by distracting visual attention, yielding a form of inattention blindness (*Strayer et al. 2003*). Their results are consistent with the earlier findings by Rumar that motorists fail to see objects in the driving environment even while directly gazing at them due to inattention blindness during cell-phone conversations (*Rumar 1990*).

2.4 SITUATIONAL AWARENESS (SA)

As discussed in the previous section, perception and attention are very important factors for safe driving (*Moore et al. 1982; Rumar 1990; Castro 2008; Gugerty 2011*). Therefore it is essential to measure motorists' attention correctly to gain insight on the driving task, and also to evaluate the effects of different factors such as cell-phone use, fatigue and drunk driving (*Gugerty 2011*). Suggesting that motorists' situational awareness (SA) is similar to motorists' attention, Gugerty has defined SA as, "the updated, meaningful knowledge of an unpredictably-changing, multifaceted situation that operators use to guide choice and action when engaged in real-time multitasking" (*Gugerty 2011*). In the context of the driving task, this meaningful knowledge can include the motorists' route location, roadway alignment, location of nearby traffic and pedestrians, fuel level, and so on. Gugerty also categorized the perceptual and cognitive processes required to maintain SA into three levels:

- Level 1: automatic, a preattentive process that occurs unconsciously and places almost no demands on cognitive resources;

- Level 2: recognition-primed, a decision processes that may be conscious for brief periods (< 1 s) and place few demands on cognitive resources; and

- Level 3: conscious, a controlled process that place heavy demands on cognitive resources (*Gugerty 2011*).

From the context of driving, Gugerty described vehicle control, such as maintaining speed and lane position as mostly an automated process, but other tasks requiring some regular conscious decisions during driving, such as lane changing or stopping at a red indication, are recognition-primed processes. At the final level, he described hazard anticipation and making navigational decisions in an unfamiliar environment during heavy traffic as requiring a controlled, conscious process (*Gugerty 2011*).

To safely accomplish the dynamic and multifaceted driving task, motorists need to perceive, identify, and correctly interpret the elements of the current traffic situation, including immediately adjacent traffic, road signs, route direction and other inputs, while being vigilant for obstacles and making predictions of near-future traffic conditions to maintain control, guidance and navigation of the vehicle *(Baumann et al. 2007).* Endsley's definition of SA incorporates the great variability of information that needs to be processed in dynamic real time tasks such as driving, air traffic control or flying. Endsley states that, "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (*Endsley 1988*). Endsley's definition of SA was expanded into three hierarchical phases (*Endsley 1995 a & b*):

- Level 1 SA involves *perception* of the elements in the environment;

- Level 2 SA is the *comprehension* of the current situation by integrating various pieces of data and information collected in Level 1 SA in conjunction with operator goals; and

- Level 3 SA involves the *projection* of future status from the knowledge of the elements and comprehension of the situation achieved in Level 1 and Level 2 SA. Level 3 SA allows the motorist to perform timely and effective decision making.

During driving, motorists need to perceive the continuously changing driving environment including road, traffic and vehicle conditions; understand the current situations; and, finally, predict the near future, Motorists need to make conscious and effective decisions to avoid hazards based on the knowledge gained in the previous two levels.

Although the two models are conceptually different, Gugerty has compared his three levels of perceptual and cognitive processes with Endsley's three levels of SA in the way that perceiving the elements of a situation (Endsley's Level 1 SA) is mostly highly automated, while comprehension and projection (Level 2 and 3) mostly use recognition-primed and controlled processes (*Gugerty 2011; Endsley 1995 a & b*).

The above discussion underlines the importance of SA, which is required for hazard anticipation and safe driving. A high degree of SA generally helps motorists to accomplish these goals as well as provide a basis for subsequent decision making and good performance in the driving task. In the context of right-hook crash scenarios, a high degree of SA could help motorists to be aware of bicyclists in the adjacent lane, predict their future maneuvers, and make decisions based on this information to safely accomplish right-turn maneuvers at signalized intersections.

2.4.1 Focal and Ambient Vision

Vision is closely related with attention and driving. Schneider and others have distinguished between two modes of vision: focal vision and ambient vision (*Schneider 1967)*. Focal vision uses foveal input and serial processing for object identification. It is much more dependent on inference and higher-level cognition. The visual receptors of ambient vision are distributed across all of the visual field and retina, both in the fovea and periphery (*Leibowitz 1982; Previc 1998, Wickens 2002*). Ambient vision is relatively automatic and unconscious (*Gugerty 2011*). Leibowitz and Owens suggested that the main subtasks of driving, vehicle control or guidance, uses the automated processes of ambient vision, while other important driving subtasks, such as identifying hazards and navigation in heavy traffic, use focal vision (*Leibowitz and Owens 1977*).

Both ambient and focal vision are important for attention capturing, good SA and safe driving. It has been found that causes of nighttime crashes can be explained by these two modes of vision (*Owens and Tyrrell 1999; Brooks et al. 2005*). Leibowitz and Owens hypothesized that, at night, focal vision degrades much more rapidly than ambient vision (*Leibowitz and Owens 1977*). Ambient vision allows the motorist to perform the main subtasks of driving. However, motorists are unaware of the severe degradation of their focal vision that helps to identify hazards. As stated by the authors (*Owens et al. 1999; Brooks et al. 2005*), the issue with the selective degradation of the two visual modes is that motorists become overconfident in their ability to perform the overall task of driving at night, which ultimately leads them to drive too fast and increases crash rates.

2.4.2 Measuring Situation Awareness (SA)

SA plays an important role in human interaction with a dynamic and changing environment in a real-time task such as driving, air traffic control or flying (*Gugerty 2011*). Although the concept of SA is better developed and applied in the aviation domain, a similar concept of SA has been applied to the driving condition as well since they share similar dynamic, environment characteristics where system input variables change over time (*Ruiqi 2005*). Over the past decade, several techniques have been developed to measure SA. Gugerty classified SA measurement techniques into two groups: 1) Online, where motorist behavior is measured in a simulated driving environment with little or no interruption and, 2) offline, when the driving scenario is not visible during behavior measurement (*Gugerty 2011*). Examples of online SA measurement include eye-tracking measures, Situation Present Awareness Method (SPAM), and Useful Field of View (UFOV) test. Offline measures include the Situation Awareness Global Assessment Technique (SAGAT), proposed and validated by Endsley (*Endsley 1995 a & b*). Other classifications to measure SA include direct and indirect measures or subjective and objective measures. In direct measures, participants are asked to recall events from their experience (*Gugerty 2011*), whereas indirect measures assess SA from the subject's performance. For example, Sarter and Woods described an indirect measure of SA where the time to detect irregularities in an environment was the measure of SA (*Gonzalez and Wimisberg 2007; Sarter and Woods 1992*). Subjective measures involve assigning numerical value to the quality of SA during a particular period and rely on a subject's self-assessment of SA (Jones 2000). Conversely, objective measures rely on querying participants to recognize a situation and then comparing their views of the situation with reality (*Gonzalez and Wimisberg 2007; Endsley 2001*). SAGAT by Endsley is an example of a direct and objective measure of SA (*Endsley 1995 a & b*).

Physiological techniques, such as P300 and eye-tracking devices, have been used for almost 40 years to monitor and measure motorists' glance patterns and determine whether information is registered cognitively. Researchers mostly record saccades or overt eye movements and fixations with the eye tracker as a proxy for determining the focus of the motorist's attention. The most common variable measured in this system is dwell time or percentage of time fixating on specific area of interest (AOI). Gugerty justified that fixation is an acceptable measure to track motorists' focal attention because while driving motorists need to gather information from about 270° around them with head movements and large saccades (*Gugerty 2011*). However, the drawback with eye tracking is that it provides information on whether elements in the environment are perceived and processed by subjects, but it cannot determine how much information remains in memory, whether the information is registered correctly, or what comprehension the subject has of those elements (*Endsley 1995 a & b*).

The most widely used offline SA technique is the SAGAT, which provides an evaluation of SA based on the operator's objective opinion. In SAGAT, all of the operator's displays are made temporarily blank during periodic, randomly-timed freezes in a simulation scenario and memory-based queries are directed at the operator to assess his knowledge of what was happening at that time. Queries are determined based on an in-depth cognitive task analysis across all three levels of SA defined by Endsley (*Endsley 1998*). The main advantage of SAGAT is that it measures operator SA across a wide range of elements that are important for SA in a particular system giving an unbiased index of SA. However, the main disadvantage of SAGAT is the issue of intrusiveness. It may change the phenomenon of interest, and therefore fail to provide data about the natural character and occurrence of SA. Also, this method relies on an operator's memory and therefore may not reflect a true representation of the operator's SA. Using SAGAT, Gugerty assessed SA of motorists in a low-fidelity driving simulator (*Gugerty 1997; Gugerty et al. 2004*). During the experiment, participants viewed driving scenarios that were blanked periodically and responded to questions assessing their awareness of cars about to collide with them and of cars in the blind spot.

In contrast to the offline SA measurement techniques such as SAGAT, the online techniques such as SPAM measures motorists' SA while keeping the driving scenario visible. In SPAM, an ongoing driving scenario in a simulator is paused at unpredictable times and the motorist is asked to respond to one or two questions about the scenario while keeping the scenario visible (*Durso et al. 2006*). Response time is the main variable.

The Situation Awareness Rating Technique (SART) provides a subjective rating of SA by operators (*Taylor 1989*). Through a series of bipolar scales, SART allows operators to rate a system design based on the degree to which they perceive the amount of demand on attentional resources, supply of attentional resources, and understanding of the situation provided. These scales are then combined to give an overall SART score for a given system. SART considers operators' perceived workload in addition to their perceived understanding of the situation. The main advantage of SART is the ease of use and low cost. It does not require customization for different domains and can be used both in simulation and real-world tasks. However, this method suffers from the possible influence of perceived performance and expected performance. Again, though SART was shown to be correlated with performance measures (*Selcon and Taylor 1990*), it is unclear whether this is attributable to the workload or the understanding components (*Endsley 1995 a*).

2.5 TRAFFIC CONFLICTS

According to Amundsen and Hydén, "a traffic conflict or near-crash is an observable situation in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged" (*Amundsen and Hydén 1977)*. A near miss is defined as a situation when two road users unintentionally pass each other with a very small margin, so that the general feeling is that a collision nearly occurred (*Laureshyn, 2010*). A commonly used severity indicator of traffic conflicts and near misses is the Time-to-Collision (TTC), which is defined as "the time required for two vehicles to collide if they continue at their present speeds and on the same path" (*Hayward 1972; Hydén 1987*). Many studies have used TTC to estimate the number and severity of conflicts (*Hoffmann et al. 1994; Hyden 1996; Minderhoud et al. 2001; Vogel 2003*). However, as Laureshyn stated that TTCs can be used as an indicator only if road users are on a collision course (i.e., if they continue without changes) a collision will occur (*Laureshyn 2010*). It is a continuous measure and can be calculated for any moment as long as the vehicles are on a collision course. The minimum Time-to-Collision is represented by the minimum TTC value (TTC_{min}), which is defined as "the minimum time distance between two vehicles during the collision avoidance process" (*van der Horst 1984*). The TTC_{min} will be zero when a collision occurs.

While evaluating the threshold value of TTC, Brown found that a TTC threshold value of 1.5 seconds is a reasonable time-based index of hazard (*Brown 1994*). To develop the Surrogate Safety Assessment Model (SSAM) for deriving surrogate safety measures for traffic facilities from data output by traffic simulation models, Gettman et al. stated that "conflicts with TTC values larger than 1.5 seconds are not generally considered in the safety community to be "severe" enough events for recording in a traditional field conflict study" (*Gettman et al. 2008*). Sayed et al. calculated traffic-conflict frequency and severity standards for signalized and unsignalized intersections using the data collected from 94 conflict surveys, in which the standards showed the relative comparison of the conflict risk at various intersections (*Sayed et al. 1999*). They presented a ROC (risk of collision) score, which was defined as "a subjective measure of the seriousness of the observed conflict and is dependent on the perceived control that the driver has over the conflict situation, the severity of the evasive maneuver and the presence of other road users or constricting factors which limit the driver's response options" (*Sayed et al. 1999*). Table 2.4 presents a relationship between the TTC (s) value and ROC score present by Sayed et al. and cited in Saunier (*Sayed et al. 1999; Saunier 2013*).

Table 2.4: TTC and ROC Score

TTC and ROC scores	Time to collision (TTC) (sec)	Risk of collision (ROC)
1	1.6-2.0	Low Risk
2	1.0-1.5	Moderate Risk
3	0.0-0.9	High Risk

2.6 SUMMARY

It is worth noting that although the incident of right-turning vehicle crashes with bicycles appears in the literature with some frequency (*Wachtel and Lewiston 1994; Weigand 2008; Summala 1988*), little substantive research has been conducted on this topic. The reason for limited research on this specific crash type could be explained in several ways, including:

- National crash statistics and hospital records are quite limited regarding variables necessary to fully understanding this crash scenario (*Thom and Clayton 1993*). They typically involve persons killed or injured; accident time (month, day, week, hour); vehicle type (large truck, passenger car, light truck, motorcycle); site (province, municipality, type of road and junction); speed limit; restraints used; circumstances of accident (weather, light condition); participants (sex, road user and age group); influence of alcohol; type of driving license; and diagrams and classification of crash types (*Thom and Clayton 1993; NHTSA 2011*). It is, at best, very difficult to infer the behavior of each party (their paths, directions and turns) from data sets of this type. Therefore, the total number of right-hook crashes occurring every year in the U.S. cannot be determined with certainty from the existing data sources.

- Although state-based crash analysis and reporting systems provide crash data for bicycle fatalities and injuries, including their types at different intersections around the state, the frequency of reported crashes can be low (*ODOT 2011; Hunter et al. 1996*). Since the motorists involved in crashes are responsible for submitting crash report forms, it is not always guaranteed that all qualifying crashes are reported to the recordkeeping authorities (*ODOT 2011*). One study found that less than two-thirds of bicycle-motor vehicle crashes were reported in state motor-vehicle files, though all of those were serious enough to require emergency room treatment (*Hunter et al. 1996*). For example, in 2009, nearly 200,500 people were treated for bicycle-related injuries occurring in traffic, representing a rate of 66 injuries per 100,000 people. But 518,750 people were transferred to hospital emergency rooms or hospitalized for bicycle-related injuries occurring in public and non-public roadways, representing a rate of 175 injuries per 100,000 people (*WISQARS 2011*). Therefore, the correct frequency of this crash type is unknown in state-level data as well.

- The history of bicycling in the U.S. as a mode of travel is fairly recent when compared to Europe and many other countries in the world. As bicycling is becoming more popular in U.S. cities, more safety-related issues are emerging, motivating new research needs (*Korve and Niemeier 2002; Weigand 2008*).

This literature review can be summarized into the following key points that reveal important gaps in the existing research on right-hook crashes at signalized intersections:

- Although some studies analyzed motorists' and bicyclists' behavior during crashes with right-turning vehicles, as interpreted by crash data, no in-depth study was found that specifically analyzed various factors contributing to right-hook crashes and potential countermeasures. In addition, there is a gap in the literature that could assess motorists' and bicyclists' SA in the crash environment, which can shed light on causal factors behind this crash type.

- A better understanding of crash causality is very important to identify potential countermeasures for mitigating that crash type. However, due to the limitations of crash data at both the national and state level, the actual characteristics of right-hook crashes are predominantly unknown. Therefore, in-depth analysis of the causal factors of this crash type is necessary. Driving simulator and eye-tracker technology can be used in this regard. Driving simulators can place motorists into crash-likely scenarios without causing any potential harm. Eye-tracker technology can provide information on motorists' eye movement. Eye-movement data collected through the eye-tracker technology provides reliable information about whether motorists could detect and perceive potential hazards during driving to avoid crashes.

- Motorists' SA and visual attention are very important for hazard anticipation and safe driving, which in turn are good measures of motorists' driving performance. Driving simulators can be used effectively to measure motorists' SA and attention, and assess motorist driving performance.

- Studies on BMV crashes at intersections shows that before turning right, motorists tend to focus their attention on the opposing, oncoming, vehicular traffic, and fail to detect the bicyclist coming from their right. Research also found that the higher speed of bicyclists overtaking the right-turning vehicle was a contributing factor to the right-hook crash. Based on that, this literature review identified that the volume of oncoming vehicular traffic, speed of bicyclists and relative position of bicyclists in the adjacent lane can potentially contribute to right-hook crashes at intersections.

- This literature review could not identify any intersection treatments implemented in the U.S. to date that has produced evidence of significantly reducing right-hook crashes at signalized intersections except bike boxes, which reduce right-hook conflicts at the onset of the green indication. The efficacy of different intersection treatments can be evaluated using the driving simulator.

3.0 OREGON CRASH ANALYSIS

As part of the research, an analysis of Oregon crash data from 2007-2011 was conducted. The first section provides an overview of bicycle crashes. The second section examines describes the process for identifying all right-hook crashes in Oregon and categorizing them.

3.1 OVERVIEW

Table 3.1 summarizes Oregon crash data from 2007-2011. In Oregon, 56 bicyclists were involved in fatal bicycle-motor vehicle crashes from 2007-2011 (*ODOT 2011*). Inspection of the table reveals that reported bicycle crash data are severity-biased (meaning that very few non-injury crashes are reported). Only 3% (29/823) of the crashes are non-injury (property damage only) as opposed to motor vehicle crashes, which have approximately 50% of the total crashes as non-injury (23,630/42,557). This is not unusual as the requirement for the bicycle crash to be reported in the state database is that it involves a motor vehicle on a road open to the public. Crashes involving vehicles and vulnerable users are more likely to involve injury.

Table 3.1: Oregon DOT reported crash summary.

Crashes		2011	2010	2009	2008	2007	5 Year Avg
Bicycle	Fatal	15	7	8	11	15	11
	Injury (A+B+C)	917	872	759	754	614	783
	PDO	30	31	35	20	28	29
	Total	962	910	802	785	657	823
Pedestrian	Fatal	48	60	38	51	50	49
	Injury (A+B+C)	795	730	613	555	526	644
	PDO	6	2	11	4	4	5
	Total	849	792	662	610	580	699
Motor Vehicle	Fatal	247	225	285	307	346	282
	Injury (A+B+C)	22,175	19,277	17,681	16,731	17,360	18,645
	PDO	24,820	22,890	21,841	23,382	25,219	23,630
	Total	47,242	42,392	39,807	40,420	42,925	42,557

In an analysis to identify candidate safety projects for ODOT, Kittelson and Associates, Inc. complied data from 2007-2011 that is summarized in Table 3.2 (*KAI 2013*). In the table, the yellow-shaded cells sum to the total in each column as well as the larger categories in the grey shade (intersections and segments). Their analysis indicates that of 4,124 bicycle-vehicle crashes, 66% occurred at intersections. Of the severe crashes (defined as fatal or injury A), approximately 61% happened at intersections. The large majority of the intersection crashes happened in urban areas (2606/2711=96%). In the urban areas, about 58% happened at unsignalized locations and 41% were at signalized intersections.

Table 3.2: Bicycle crashes, 2007-2011 by category.

	Portland Metro		Non-State Highways		State Highways		Statewide		Row Percent of Total	
	Total	Severe	Total	Severe	Total	Severe	Total	Severe	Total	Severe
Intersections	1460	118	849	66	402	37	2711	221	66%	61%
Urban	1460	118	792	56	354	31	2606	205	63%	56%
Signalized	624	46	258	20	197	20	1079	86	26%	24%
Unsignalized	836	72	534	36	157	11	1527	119	37%	33%
Rural			57	10	48	6	105	16	3%	4%
Signalized			2	0	9	1	11	1	0%	0%
Unsignalized			55	10	39	5	94	15	2%	4%
Segment	634	54	574	61	205	27	1413	142	34%	39%
Urban	634	54	491	44	157	14	1282	112	31%	31%
Rural			83	17	48	13	131	30	3%	8%
Total	2094	172	1423	127	607	64	4124	363		

Source: Kittelson and Associates, Inc. Oregon Pedestrian and Bicycle Safety Implementation Plan, Stakeholder Workshop Handouts for Breakout Session #1 *(KAI 2013)*

3.2 ANALYSIS OF POTENTIAL RIGHT-HOOK CRASHES

Further exploration of the bicycle-vehicle crashes reported in the ODOT data from 2007-2011 was conducted to identify the characteristics of intersections where right-hook crashes occur. Since vehicle and bicycle movements and directions are components of ODOT bicycle crash data *(2007-2011),* a subset of the crash data were prepared to study right-turning vehicles and through-moving bicycles. First, all combinations of vehicle movements that could be typed as a potential right-hook crash (a through bicycle and a right-turning car) were extracted from the crash database. The use of the vehicle movements as the only typing factor does not explicitly define a "right=hook" crash so they are labeled "potential right-hook" crashes. To complete type a crash as a right hook, the sequence of events and location of these events would be needed which are usually only available in crash reports (which were not available in this research). Thus, based on the recorded paths of the vehicles involved, 504 crashes were typed as likely being right-hook crashes. Of these 504, 68 of them were noted to have occurred off-roadway (i.e. on the sidewalk or other area not part of the roadway. The locations of all potential right-hook crashes in Oregon are shown on the statewide map shown in Figure 3.1. The majority of collisions are in the Willamette Valley and near population centers, as expected.

Second, at the locations where each of these crashes occurred, design and operational variables were collected (e.g., presence of bike lanes, right-turn lanes and traffic control devices), as well as injury levels where incidents occur. The information was gathered from review of the aerial photos. To obtain these photos quickly, a simple R-script was developed to extract the aerial images from Google Maps images using the latitude and longitude coordinates coded for the crash. The detailed crash data was annotated to each right-hook crash for further review (i.e., directions, movements, date, time, gender, age, address, crash id, injury levels, etc.). A sample of these images is shown in Figure 3.2.

Images were matched against data to determine in which quadrant of an intersection each crash occurred. Likewise, images were reviewed to determine the presence of bike lanes and right-turn lanes. Intersections were also explored with Google Maps and Street View to determine the traffic control devices and categorize the traffic control (traffic signal, stop sign, minor stop, yield sign, and no control). Finally, a data table, including all variables (i.e., presence of bike and right-turn lanes, traffic control devices, intersection types, injury levels and quadrants) was created.

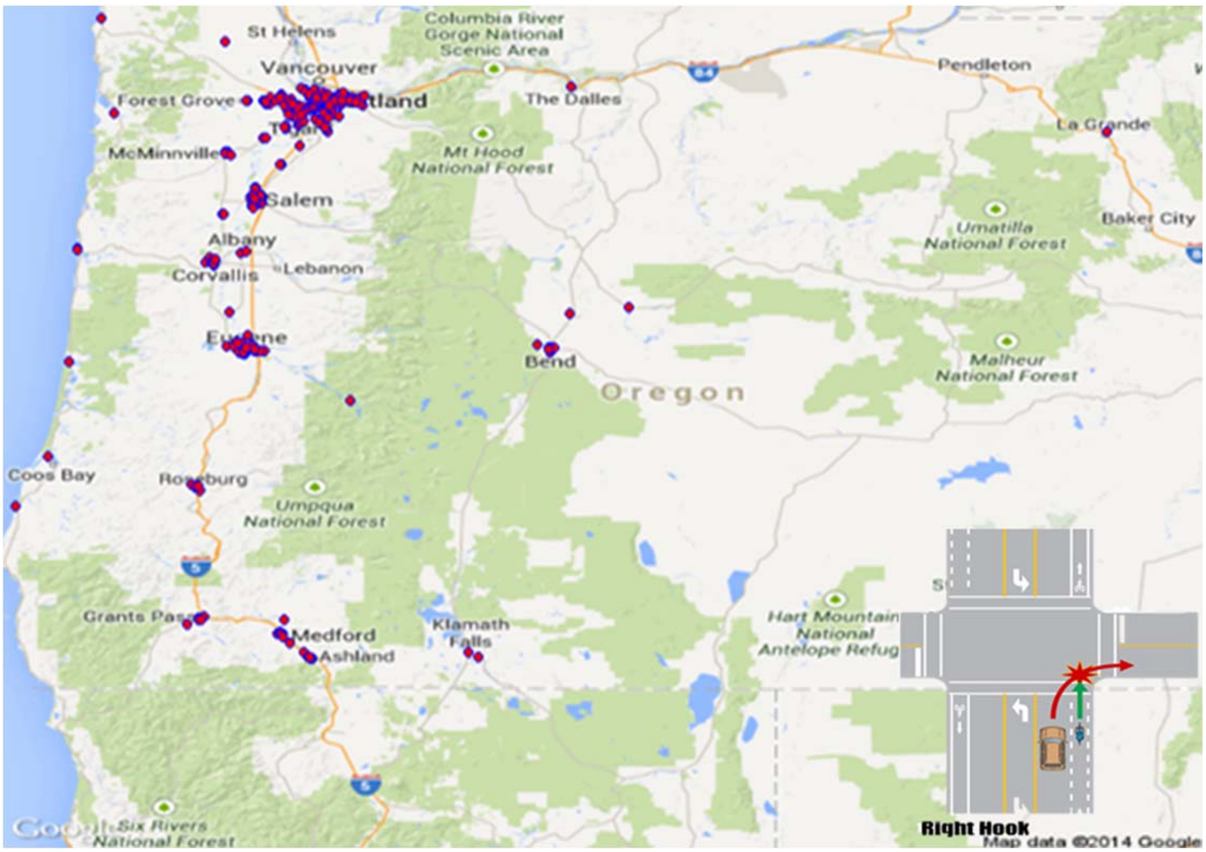


Figure 3.1: Potential right-hook crash locations in Oregon *(2007-2011).*

Figure 3.2: Sample crash data record overplotted on aerial image for right-hook crashes.

The frequency and percentage of right-hook crashes including all variables except injury levels are displayed in the following tree plot (Figure 3.3). At the center of the tree plot, the data are first split into right-hook crashes. The box shows that of the 4,072 reported bicycle-involved crashes, 504 (12.3%) of them could be typed as a right-hook crash. A total of 68 potential right-hook collisions occurred off-roadway (the majority of those (54, or 80%) happened at driveway locations. At each intersection, the presence and type of traffic control (signal, stop signs), the presence of a right-turn lane and bicycle lane were noted. This included the following conditions noted in the Figure 3.3 legend at the location of the right-hook crash:

- Bike lane (BL): A bicycle lane was present
- No Bike Lane (NBL): No bicycle lane was present
- Right Turn Lane (RTL): A right-turn lane for motor vehicles was present
- No Right Turn Lane (NRTL): No right-turn lane for motor vehicles was present

The upper part of the tree shows the breakdown of the 26% (133/504) of those right-hook crashes that occurred at driveways. The lower part of the tree plot shows the 73.6% of the right-hook crashes that occurred at intersections (371/504). Exploring the lower tree branch, the 371 crashes are allocated to the type of traffic control. The majority of intersection crashes occur at signalized intersections (72%) followed by the minor stop-controlled intersections. A small number of crashes happened at stop-controlled intersections (four-way stop) or intersections with no visible traffic control. For each traffic control type, the box below indicates whether there was a bike lane or no-right-turn lane. Focusing on the 267 crashes at intersections with traffic signals, the tree chart shows that 59% (158/267) occurred at intersections with a bicycle lane but without a right-turn lane. Another 25% occurred at intersections with no bike lane and no right-turn lane. Only a total of 16% ((26+17)/297) happened at intersections with right-turn lanes. These crashes may be occurring at the weaving area between the bicycle lane and right-turn lane and may not be right-hook type crashes. At intersections with minor stop control, a right-turn lane would not normally be provided. On the upper part of the tree plot, the breakdown of the 133 crashes that occurred at driveways is shown. Here, too, the majority of crashes (83+4)/133=65% occurred with the presence of a bike lane and no-right-turn lane.

In summary, the tree plot indicates that most recorded potential right-hook crashes occurred at signalized intersections with a bike lane and a no-right-turn lane. Part of this is maybe related to increased exposure due and the possible combinations of the designs. Probably the most important observation of the analysis is that at signalized intersections the majority of crashes occur when there is no right-turn lane provided.

Exploring the crash totals by severity can also provide some insight. The injury levels include property damage only (PDO), disabling (A), evident (B), possible (C), and fatal (K). Figure 3.4 shows the severity profile for the 504 right-hook crashes. Though they are common crash types, approximately 6.4% of the total was fatal or severe incidents. For all bicycle-involved crashes summarized in Table 3.1, 8.8% were recorded as severe (note this total includes right-hook crashes). Most recorded right-hook crashes had injury level B. The frequency of injury levels of right-hook crashes with respect to each variable is shown within each bar in Figure 3.5, Figure 3.6, and Figure 3.7. With the exception of much fewer severe injury crashes at intersections with right-turn lanes, the severity profiles appear very consistent.

Driveway – No Control

	BL		NBL	
	RTL	NRTL	NRTL	RTL
On-Road	2	49	25	1
Off-Road	0	34	17	0
Total	2 (1.5%)	83 (64.8%)	42 (32.8%)	1 (0.8%)

Driveway – Minor Stop

BL		NBL		
RTL	NRTL	NRTL	RTL	
0	2	0	0	On-Road
0	2	1	0	Off-Road
0 (0%)	4 (80%)	1 (20%)	0 (0%)	Total

No Control	
On-Road	77
Off-Road	51
Total	128 (96.2%)

Driveway	
On-Road	79
Off-Road	54
Total	133 (26.4%)

Minor Stop	
On-Road	2
Off-Road	3
Total	5 (3.7%)

	Bicycle-Car Crash	Potential Right Hook Crash
On-Road	3650	436
Off-Road	422	68
Total	4072	504 (12.4%)

4-Way Stop	
On-Road	14
Off-Road	0
Total	14 (3.8%)

Traffic Signals	
On-Road	258
Off-Road	9
Total	267 (71.9%)

Intersection	
On-Road	357
Off-Road	14
Total	371 (73.6%)

Minor Stop	
On-Road	83
Off-Road	5
Total	88 (23.7%)

No Control	
On-Road	2
Off-Road	0
Total	2 (0.5%)

Intersection – 4-Way Stop

	BL		NBL	
	RTL	NRTL	NRTL	RTL
ON-Road	0	3	10	1
Off-Road	0	0	0	0
Total	0 (0%)	3 (21%)	10 (71%)	1 (7%)

Intersection – Traffic Signals

BL		NBL	
RTL	NRTL	NRTL	RTL
22	154	65	17
4	4	1	0
26 (9.7%)	158 (59.2%)	66 (24.7%)	17 (6.4%)

Intersection – Minor Stop

BL		NBL	
RTL	NRTL	NRTL	RTL
0	53	27	3
0	3	2	0
0 (0%)	56 (63.6%)	29 (33%)	3 (3.4%)

Intersection – No Control

BL		NBL		
RTL	NRTL	NRTL	RTL	
0	0	2	0	ON-Road
0	0	0	0	Off-Road
0 (0%)	0 (0%)	2 (100%)	0 (0%)	Total

Bike Lane | No Bike Lane | Right Turn Lane | No Right Turn Lane

Figure 3.3: Tree plot of potential right-hook crashes by traffic control device, the presence of the bike lane, and the presence of right-turn lane.

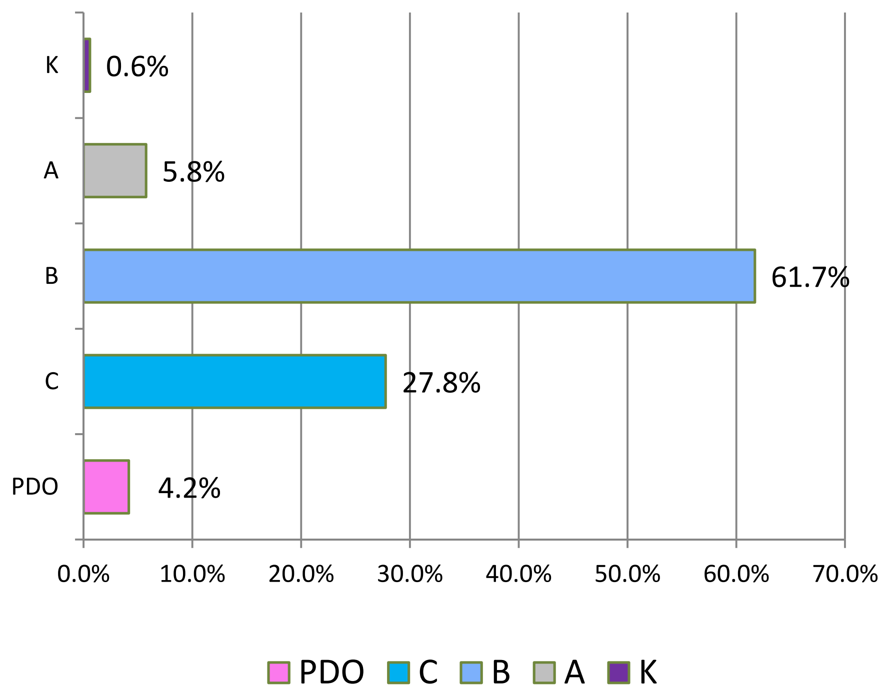


Figure 3.4: Severity profile of the right-hook crash (n=504).

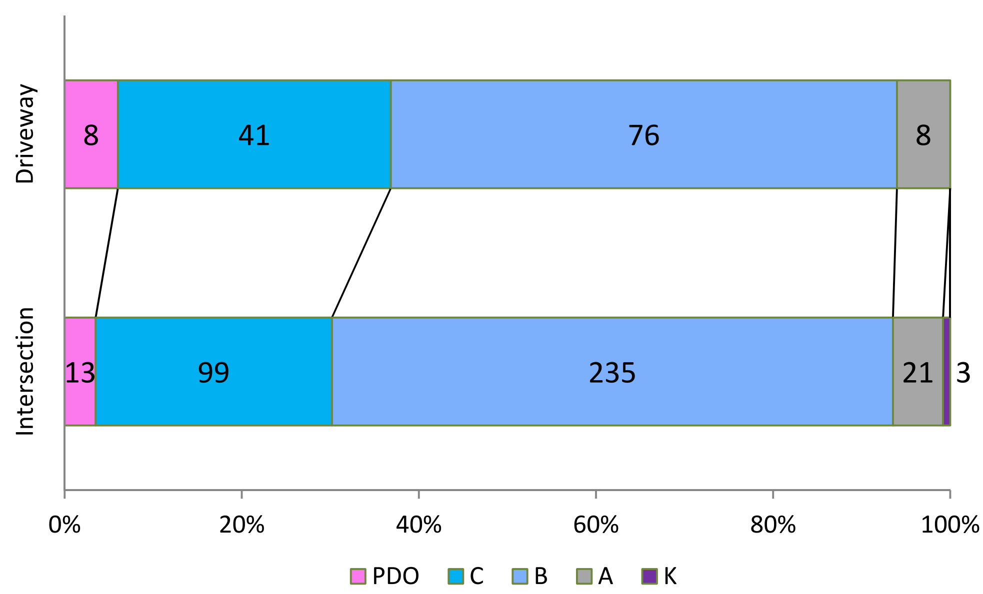


Figure 3.5: Severity profile of the right-hook crash at intersections (n=371) and driveways (n=133).

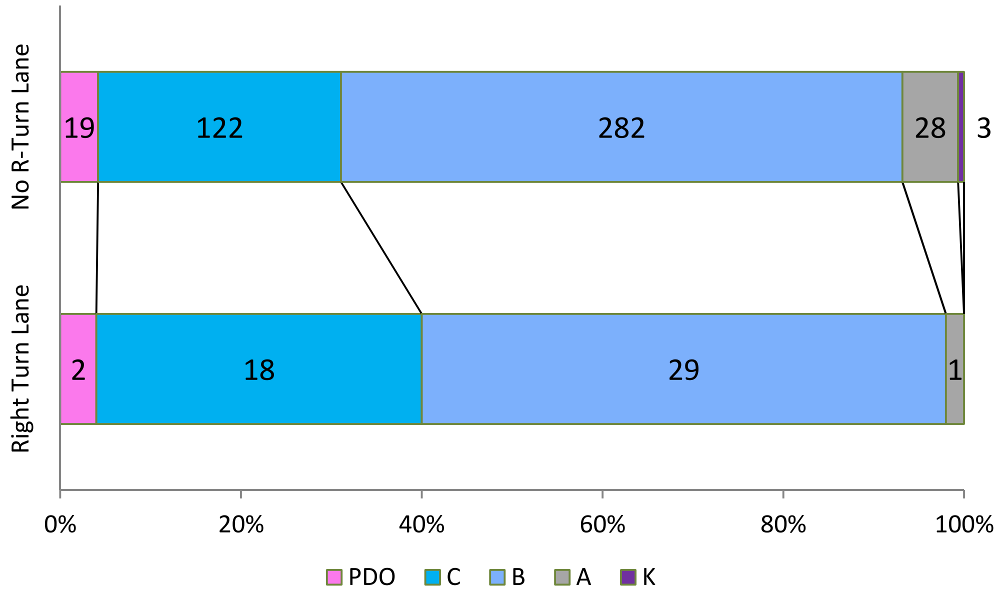


Figure 3.6: Severity profile of the right-hook crash at intersections without right-turn lanes (n=454) and with right-turn lanes (n=50).

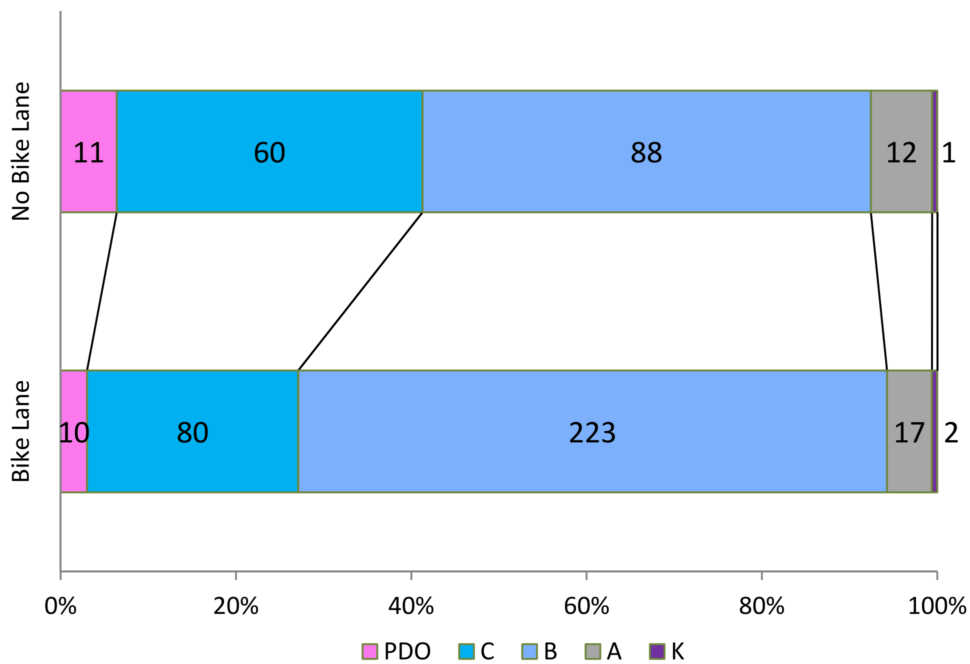


Figure 3.7: Severity profile of the right-hook crash at intersections without bike lane (n=172) and with bike lane

3.3 SUMMARY

In Oregon, the reported crash data indicates that the right-hook crash is a common BMV crash type at urban intersections; many of these crashes do result in severe injury. The research reviewed 504 potential right-hook crashes identified from vehicle movement data out of the 4,072 total crashes identified in ODOT bicycle crash data *(ODOT 2011).* Potential right-hook crashes accounted for 12.3% of all crashes during this time period. Though it is a frequent crash type, the majority of recorded crashes were moderate (62%) severity. A further 28% were minor injury and 4% were no injury. Still, 7% of the crashes were severe or fatal injury and represent and opportunity to improve safety for bicyclists. Each right-hook crash was reviewed in detail to identify the type of intersection traffic control and lane configurations. Intersection locations accounted for 74% of right-hook crashes; the remaining 26% of crashes occurred at driveways. The most common intersection configuration for right-hook crashes was a bike lane to the right of a through motor vehicle lane with no right-turn lane. This configuration accounted for 59% of total crashes at signalized intersections and 64% of total crashes at minor stop intersections.

4.0 METHODOLOGY

The hardware and software associated with the Oregon State University (OSU) driving simulator and the eye tracker are described as well as the types of data collected for Experiment 1 and 2. Additionally, the experimental protocol including the process for recruitment of subjects, the sequence of activities participants were directed to perform during the experiments and the pilot study of the experimental protocols is detailed.

4.1 DRIVING SIMULATOR

The 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 capable of rotating ±4 degrees. 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 *(OSU 2011).* Researchers build the environment and track subject drivers from within the operator workstation shown in Figure 4.1, which is out of view from participants within the vehicle.

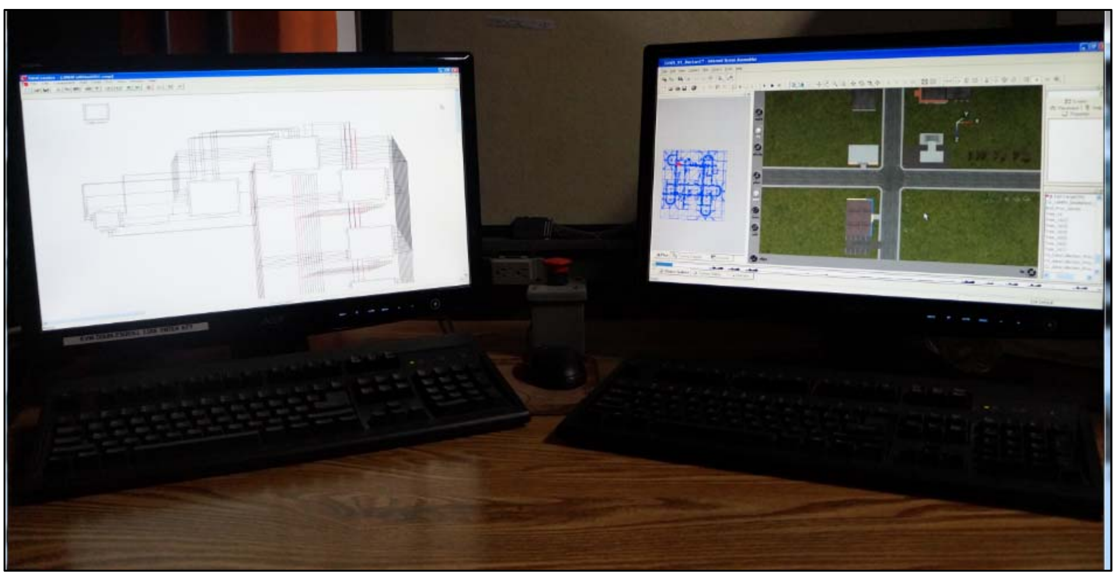


Figure 4.1: Operator workstation for the driving simulator.

Three liquid crystals on silicon projectors with a resolution of 1,400 by 1,050 are used to project a front view of 180 degrees by 40 degrees. These front screens measure 11 feet by 7.5 feet. 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 the projected graphics is 60 Hz. Ambient sounds around the vehicle and internal sounds to the vehicle are modeled with a surround sound system. The computer system consists of a quad core host running Realtime Technologies SimCreator Software with an update rate for the graphics of 60 Hz. The simulator software is capable of capturing and outputting highly accurate values for performance measures such as speed, position, brake and acceleration. Figure 4.2 shows views of the simulated environment created for this experiment from inside (left) and outside (right) the vehicle.

Figure 4.2: Simulated environment in OSU driving simulator.

The virtual environment was developed using Simulator software packages, including Internet Scene Assembler (ISA), Simcreator and Google Sketchup. The simulated test track was developed in ISA using Java Script-based sensors on the test tracks to change the signal indication and display dynamic objects, such as a bicyclist approaching the intersection in the adjacent bicycle lane, an oncoming vehicle turning left or a conflicting pedestrian crossing the intersection, based on the subject vehicle's presence.

4.1.1 Simulator Data

The following parameters on both subject vehicle and dynamic objects were recorded at roughly 10 Hz (10 times a second) throughout the duration of the experiment:

- Time – To map the change in speed and acceleration with the position on the roadway;
- Instantaneous speed of subject vehicle – To identify changes in speed approaching an intersection;
- Instantaneous position of subject vehicle – To estimate the headways and distance upstream from the stop line;
- Instantaneous acceleration/deceleration – To identify any acceleration or deceleration approaching the intersection;
- Instantaneous speed of dynamic vehicle – To record the speed approaching an intersection; and
- Instantaneous position of dynamic object– To locate the distance upstream from the stop line and also to calculate the headway of the subject vehicle.

4.1.2 Simulator Sickness

Simulator sickness is a phenomenon where a person exhibits symptoms similar to motion sickness caused by a simulator *(Fisher et al. 2011; Owens and Tyrrell 1999*). The symptoms are often described as very similar to that of motion sickness, and can include headache, nausea, dizziness, sweating, and in extreme situations, vomiting. While there is no definitive explanation for simulator sickness, one widely accepted theory, cue conflict theory, suggests that it arises from the mismatch of visual motion cues and physical motion cues, as perceived by the vestibular system *(Owens and Tyrrell 1999).*

4.1.3 Eye-Glance Data

Eye-tracking data were collected with the Mobile Eye-XG platform from Applied Science Laboratories (ASL) as displayed in Figure 4.3. This platform allows the user to have both unconstrained eye and head movement. A sampling rate of 30 Hz was used, with an accuracy of 0.5-1.0 degrees *(OSU driving simulator, 2011).* The participant's gaze was calculated based on the correlation between the participant's pupil position and the reflection of three infrared lights on the eyeball. 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 to another point. The Mobile Eye-XG system records a fixation when the participant's eyes pause in a certain position for more than 100 milliseconds. Quick movements to another position (saccades) are not recorded directly but are calculated based on the dwell time between fixations. For this research, the saccades were not analyzed due to the research questions being considered.

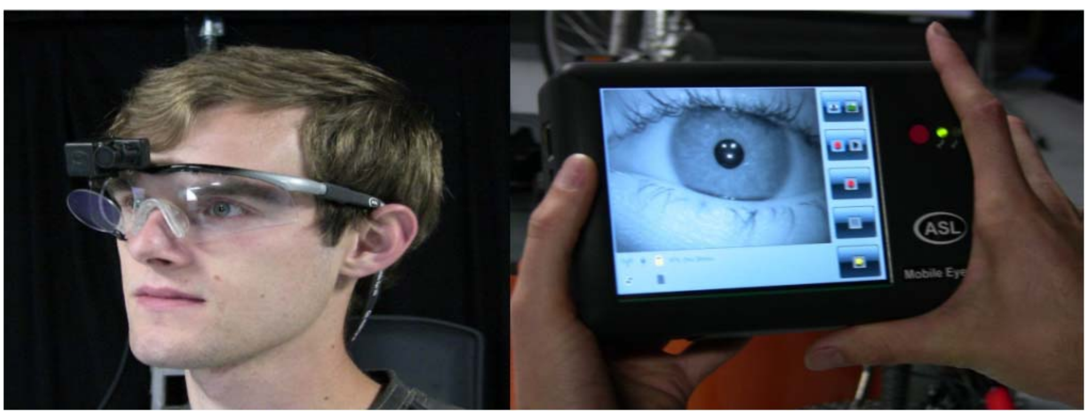


Figure 4.3: OSU researcher demonstrating the Mobile Eye XG Glasses (left) and Mobile Recording Unit (right).

4.2 DRIVING SIMULATOR EXPERIMENTAL PROTOCOL

The experimental procedure was carefully designed to reduce the occurrence of simulator sickness, for example, by providing long tangent sections between right-turns or providing small breaks between driving successive grids while asking the SA questionnaire. The entire data collection process was designed to insure that all necessary information was recorded efficiently.

This section describes the step-by-step procedures of the driving simulator study, as conducted for each individual participant.

4.2.1 Recruitment

A total of 113 individuals, primarily from the community surrounding Corvallis, OR, participated as test participants in Experiment 1 (67) and Experiment 2 (46). The population of interest was licensed Oregon drivers; therefore, only licensed Oregon drivers with at least one year of driving experience were recruited for the experiment.

In addition to Oregon licensure, participants were required to not have vision problems, and be physically and mentally capable of legally operating a vehicle. Participants also needed to be deemed competent to provide written, informed consent. Recruitment of participants was accomplished through the use of flyers posted around campus and emailed to different campus organizations and a wide range of email listservs. Older participants were specifically recruited by emails using the Center for Healthy Aging Research (CHAR) registry (LIFE Registry). This registry includes people aged 50 or over who reside in Oregon and wish to volunteer for research studies.

Researchers did not screen interested participants based on gender until the quota for either males or females had been reached, at which point only the gender with the unmet quota was allowed to participate. Although it was expected that many participants would be OSU students, an effort was made to incorporate participants of all ages within the specified range of 18 to 75 years. Throughout the entire study, information related to the participants was kept under double-lock security in compliance with accepted Institutional Review Board (IRB) procedures. Each participant was randomly assigned a number to remove any uniquely identifiable information from the recorded data.

4.2.2 Informed Consent and Compensation

Upon the test participant's arrival to the laboratory, the informed consent document that was approved by OSU's IRB was presented and explained. It provided the participant with the opportunity to have an overall idea of the entire experiment and ask any questions regarding the test. The informed consent document included the reasoning behind the study and the importance of the participant's participation. In addition, the document explained the test's risks and benefits to the participant. Participants were given $20 compensation in cash for participating in an experimental trial after signing the informed consent document. Participants were also clearly informed that they could stop the experiment at any time for any reason and still receive full compensation. Participants were not told of the specific research objective or the associated hypotheses.

4.2.3 Prescreening Survey

The second step of the simulator test was a prescreening survey targeting participants' demographics, such as age, gender, driving experience and highest level of education, as well as their prior experience with driving simulators and motion sickness. In addition to the demographic information, the survey included questions in the following areas:

- Vision – Participants' vision was crucial for the test. Participants were asked if they use corrective glasses or contact lenses while driving. It was insured during the test drive that the participants were able to clearly see the driving environment and read the visual instruction displayed on the screen to stop the driving.
- Simulator sickness – Participants with previous driving simulation experience were asked about any simulator sickness they experienced. If they had previously experience simulator sickness, they were encouraged not to participate.
- Motion sickness – Participants were surveyed about any kind of motion sickness they had experienced in the past. If an individual had a strong tendency towards any kind of motion sickness, they were encouraged not to participate in the experiment.

4.2.4 Calibration Drive

A test drive followed the completion of the prescreening survey. At this stage, motorists were required to perform a three- to five-minute calibration drive to acclimate to the operational characteristics of the driving simulator, and to confirm if they were prone to simulator sickness. Once seated in the vehicle for the test drive, participants were allowed to adjust the seat, rear-view mirror and steering wheel to maximize comfort and performance while driving in the experiment. Participants were also instructed to drive and follow all traffic laws that they normally would. The test drive was conducted on a generic city environment track with turning maneuvers similar to this experiment so that participants could become accustomed to both the vehicle's mechanics and the virtual reality of the simulator.

In the case that a participant reported simulator sickness during or after the calibration drive, they were excluded from the experimental drives.

4.2.5 Eye-Tracking Calibration

After the participants met the inclusion criteria and acclimated to the operational characteristics of the driving simulator during the calibration drive, then the researchers instrumented them with a head-mounted eye tracker. Participants were directed to look at different locations on a calibration image projected on the forward screen of the driving simulator (Figure 4.4). If the eye-tracking equipment was unable to perform the calibration, which depended on eye position and other physical attributes, then the experiment was not continued.

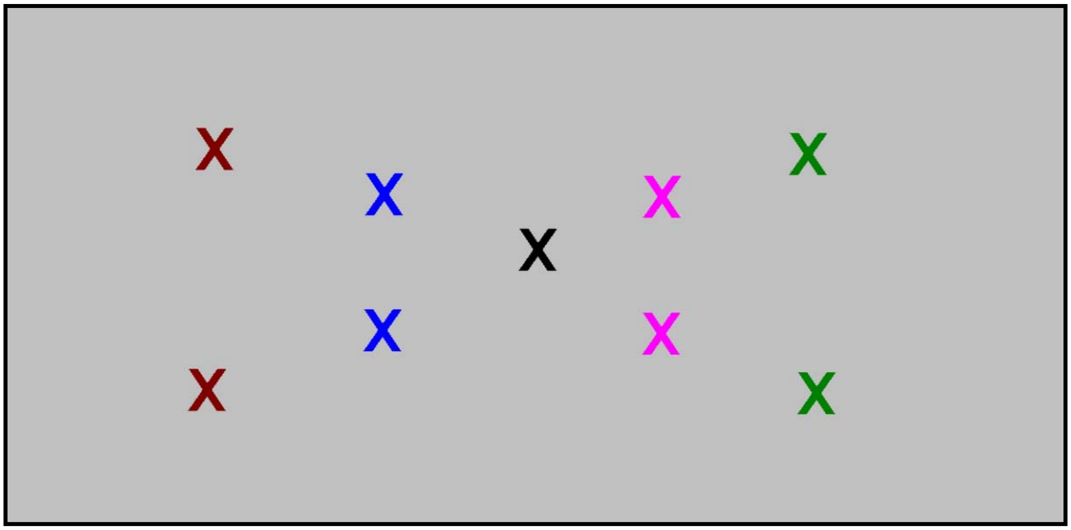


Figure 4.4: Eye-tracking calibration image.

4.2.6 Experimental Drive

After the motorist's eyes were calibrated to the driving simulator screens, they were given a brief instruction about the test environment and the tasks they were required to perform.

4.2.6.1 Experiment 1

The experiment was divided into seven grids. Participants were asked to fill out the SA questionnaire at the end of the first six grids. The virtual driving course itself was designed to take the participant 20 to 30 minutes to complete. The entire experiment, including the consent process, eye-tracker calibration and post-drive questionnaire, lasted approximately 50 minutes.

4.2.6.2 Experiment 2

The experiment was divided into six grids. Participants were asked to operate the radio in different ways at the end of the first five grids. The virtual driving course itself was designed to take the participant 20 to 30 minutes to complete. The entire experiment, including the consent process, eye-tracker calibration and post-drive questionnaire, lasted approximately 45 minutes.

4.2.7 Post-Drive Survey

As the final step of the experiment, drivers were asked to respond to several questions in a post-drive online survey.

4.2.7.1 Experiment 1

After providing a consistent definition for a right-hook crash, the post-drive survey focused on the following categories of questions:

- Familiarity with right-hook crash – Had motorists heard the phrase "right-hook crash" before participating in this study and had they ever been involved in a right-hook crash while driving a car or riding a bicycle?

- Motorist behavior at intersections – Do they commonly look for bicyclists in an adjacent bicycle lane when turning right at an intersection and, if so, how do they scan for the bicyclist?

4.2.7.2 Experiment 2

The post-drive survey assessed two general categories of questions:

- Comprehension of treatments – Specifically, how would the motorist interpret the meaning of different bicycle lane, traffic sign, and geometric configurations? Preference for treatments – Specifically, which treatment types did motorists prefer?

4.2.8 Pilot Study

Before conducting the full-scale experiment, a pilot study was conducted with five participants (two males and three females) in order to receive feedback on experimental procedures and the experimental scenarios. Valuable insight was provided on the effectiveness of the planned research design. Feedback from pilot study participants were used to modify the wording of the task command and SA questionnaire. Data analysis also helped to calibrate the worst-case experimental factor combination to be used in the crash-likely scenario.

4.3 DATA REDUCTION

After collecting participants' eye-movement data with the eye tracker, fixation data were analyzed by AOI polygons with the ASL Results Plus software suite. For this process, researchers watched each collected approach video (20 per participant) and drew AOI polygons on individual video frames in a sequence separated by intervals of approximately five to 10 frames. Once the researcher manually situated each AOI, an "Anchor" was created within the software. The distance and size differences of the AOIs between these Anchors was interpolated by the Results Plus software, to ensure that all fixations on the AOIs (i.e., pedestrians, bicyclists, mirrors and oncoming vehicles) were captured.

Figure 4.5 is a screen shot of the ASL Results Plus software. This is an example of a video that has been coded with AOIs. At this particular moment in time, the motorist was fixating on a bicyclist who he initially detected in the rearview mirror before turning right (right edge of the figure identified by a yellow rectangular AOI and red crosshairs).This figure also includes heat maps (orange-yellow circular patterns) for the conflicting pedestrian AOI crossing the intersection and the side traffic signal AOI with a green indication in the motorist's field of view.

Figure 4.5: Participant fixating on the bicyclist before turning right.

Another example of a participant fixating on a conflicting pedestrian AOI (center of the figure identified by a pink rectangular AOI and red crosshairs) at the crosswalk is shown in Figure 4.6. This figure exemplifies a complex driving scenario where the motorist had to scan for the oncoming vehicular traffic, a crossing pedestrian in the conflicting cross walk, and the bicyclist riding in front of him before turning right at the intersection. Figure 4.7 demonstrates different AOIs, such as rearview (RV) mirror, traffic signal and that motorists fixated before turning right at an intersection.

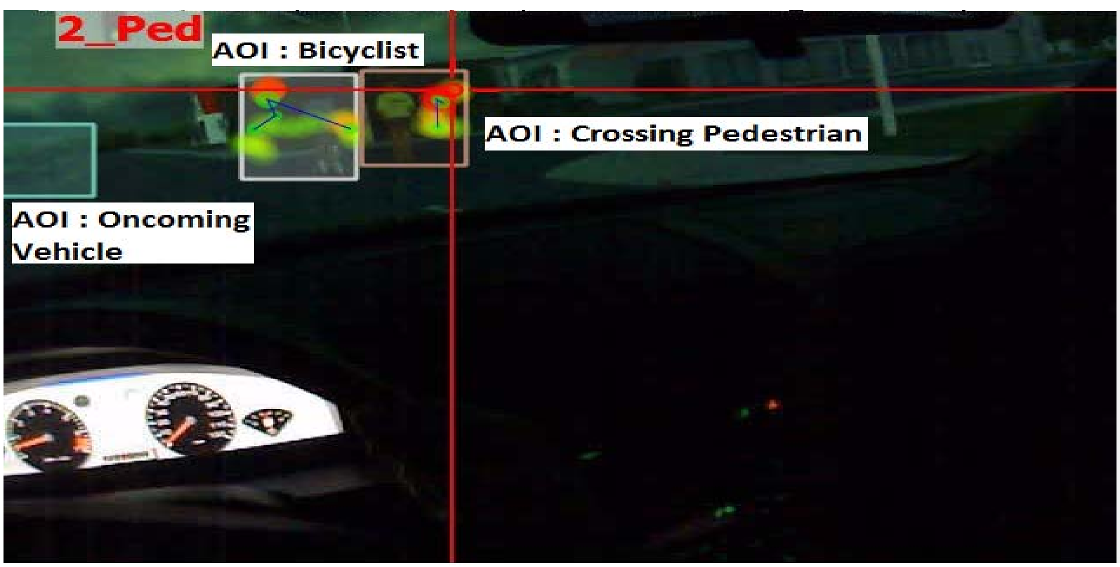


Figure 4.6: Participant fixation pattern in presence of bicyclist, pedestrian and oncoming vehicle before initiating a right-turn.

Figure 4.7: Examples of AOIs participants fixated on before turning right.

Researchers analyzed motorist's eye-tracking data starting from the point when the participant approached the intersection and continued until the participant completed the right-turn maneuver. Therefore, all of the objects of concern related to the current research questions appear before the right-turning maneuvers were completed.

Once the AOIs were coded for each individual video file, output spreadsheets of all the fixations and their corresponding AOIs were produced using the ASL Results Plus software. Fixations outside of coded AOIs were universally defined as OUTSIDE and were not analyzed further. Researchers exported these .txt spreadsheets and imported them into different analysis packages (e.g., Excel and SPSS) for further analysis.

Table 4.1 presents an example of a portion of one participant's summary data set exported from the Results Plus software at a single approach with oncoming vehicles, a pedestrian crossing in the conflicting crosswalk, and a bicyclist approaching from behind the motorist. This table summarizes the fixations during a single 25-second approach video and includes the number of fixations, total fixation durations, average fixation durations, and time of the first fixation within each AOI created during an intersection approach and right-turn maneuver. Saccades were not analyzed. A 25-second approach video was analyzed for every participant at every intersection. Figure 7.1 shows examples of different AOIs that motorists fixated on during the experiment.

Table 4.1: Example AOI summary table.

AOI Name	Description	Fixation Count	Total Fixation Duration (s)	Average Fixation Duration (s)	First Fixation Time (s)
Bike_Bk	Bicyclist approaching from the behind	2	0.43	0.215	106.8
Ped	Conflicting pedestrian at the crosswalk	12	5.47	0.456	88.09
Car	Oncoming vehicle turning left at intersection	6	2.51	0.837	94.70
Signal_main	Overhead traffic signal	1	0.160	0.16	107.86
Signal_side	Right-side traffic signal	0	0	0	0
RV_Mirror	Rear-view mirror	4	0.58	0.145	81.74
Side_Mirror	Right-side mirror	8	1.84	0.230	79.97
Outside	Any other area	282	88.19	0.313	2.156

4.4 FIELD VALIDATION

The research team considered which elements of the high-fidelity data collected from the simulator could also be observed in the field. Many of the driver performance measures have previously been established or validated. For this research on the right-turning conflict, possible measures included the speed of the right-turning vehicles, the speed of bicyclists, and the time gaps selected by drivers. The speed selection of right-turns is not well modeled in the simulator so would not be an ideal driver performance or behavior metric for validation. The speed of the bicyclist is fixed at either 12 or 16 mph in the simulator, so there would be no variation in the speeds to validate. The time to collision measured in the simulator, however, is an important metric and could be compared to the post encroachment time measured in the field. As mentioned previously, the time-to-collision measure is a continuous measurement that changes as vehicles decelerate to avoid collisions. In the driving simulator, the speed of the bicycle is fixed. The measured TTC in the simulator is for the instant the right-turn vehicle crosses the bicycle lane. This same occurrence was measured in the field and compared. The primary difference is that bicycles could decelerate which complicates the measurement of TTC. Thus, in the field the post encroachment time (PET) was measured. This is defined at the difference in time for vehicles to occupy the same space.

To validate driver performance in the simulator, video data were collected for a 144-hour period between November 11, 2014, and February 12, 2015, at the intersection between N. Going Street and N. Interstate Avenue in Portland, OR. This intersection was chosen after a careful consideration of many intersections that most closely met the intersection in the simulator. In order to most closely match the simulator driving environment, the intersection needed to be signalized with two vehicle lanes, a striped bicycle lane, without a right-turn lane, and without a bike box. To maximize the number of samples collected, additional criteria was that there should be reasonable through-bicycle volumes and right-turning vehicles, and a place to mount the video cameras. The intersections considered are shown in Table 4.2

Out of these intersections, N. Going and Interstate was chosen because the volume of right-turning vehicles and through-moving bicycles on Interstate was relatively high, which would make it possible to record interactions between bicycles and vehicles. N. Interstate Avenue does differ from the simulator intersection. Rather than two through lanes, there is a left-turn lane in both the northbound and southbound directions, which is different from the simulator setting. The conflicting left turn was not permissive, meaning the right-turning vehicles did not interact with left-turning vehicles as in the simulator.

Table 4.2: Intersections considered for field validation.

Intersection	Intersection
N Interstate Ave & N Going St, Portland, OR	SW Pacific Hwy & SW McDonald St, Tigard, OR
N Interstate Ave & N Rose Parks Way, Portland, OR	SW 14th Ave & NW Monroe Ave, Corvallis, OR
NE Broadway & NE 7th Ave, Portland, OR	SW 9th Ave & NW Monroe Ave, Corvallis, OR
NW 14th Ave & NW Everett, Portland, OR	SW 5th Ave & NW Monroe Ave, Corvallis, OR
SW Murray Blvd & SW Brockman St, Beaverton, OR	SW 35th Ave & SW Western Blvd, Corvallis, OR
SW Farmington & SW Murray Blvd, Beaverton, OR	NW Highland Dr & NW Walnut Blvd, Corvallis, OR
N Interstate Ave & N Going St, Portland, OR	SW Pacific Hwy & SW McDonald St, Tigard, OR

4.4.1 Field Setup

Two video cameras were attached to the power pole on the southeastern corner of the intersection. They captured footage side by side, eliminating the need to sync the video. The footage was reviewed and analyzed at a later date. They provided separate views that allowed continuous observation of bicyclists and motorists. The first view showed a right-turning vehicle crossing the bike lane to N. Going Street and a through-moving bicycle passing the intersection as well as the crosswalk on Going. The second view showed bicyclist and motorist movements approaching the intersection as well as the crosswalk on N. Interstate Avenue (Figure 4.8).

Figure 4.8: Screen capture of the video data collection, looking North Going Street (left) and North Interstate Avenue (right).

4.4.2 Extracting PETs and Bicyclists' Speed from the Video

To confirm that the driver in the simulator had a real-world experience in the interaction with the bicyclist, researchers investigated whether Post Encroachment Time (PET) (the time required for a bicyclist to reach the conflict point where the vehicle crossed the path of the bike lane) compared to the simulator environment (which measured the time-to-collision (TTC) value measured at the intersection.

All of the video was reviewed to identify all right-turning vehicle and bicycle interactions. The speed of bicyclists and PETs were extracted from the video using a manual frame-by-frame analysis. To measure bicyclists' speed, the width of the crosswalk on North Interstate Avenue and the time period when bicyclists were passing the crosswalk were collected. The width of the crosswalk was equal to 12 feet (10 feet between markings and 1 foot for each stripe). Using the SMPlayer program, the frame numbers of the time was measured by counting the number of frames, and then converted into the milliseconds. In the SMPlayer each second, depending on the length of the footage, consisted of 30 or 20 frames, so each frame equaled 33.3 or 50 milliseconds, respectively. The same method was conducted to measure PETs between bicyclists and right-turn motorists. When the vehicle reached the point in the middle path of the bike lane, we started counting the number of frames until the bicyclist reached that conflict point. Finally, PETs were calculated in milliseconds by multiplying the number of frames into their equivalent milliseconds (33.3 or 50). Figure 4.9 displays how the PET was measured.

Figure 4.9: Post Encroachment Time (PET) = ($T_2 - T_1$).

5.0 RESEARCH DESIGN

As highlighted in the literature review chapter, a safe right-turning maneuver requires that the motorist complete at least two independent tasks: (1) look and detect the bicyclist, (2) make the appropriate decision based on that information and corresponding conditions at the intersection. Further, quantitative information on the effect of various design treatments on driver performance relative to these tasks are limited.

To address these issues, the research team designed and developed a two-stage experimental approach. In Experiment 1, the subjects were run through an experiment designed to expose the most likely scenarios that result in a right-hook crash. In Experiment 2, design treatments and controls were built into the environment and tested under these high-load conditions.

This chapter provides a detailed description of the experimental design, selection of participants, task selection and implementation, and experimental procedure of this driving simulator study. The design of each experiment is presented separately.

5.1 DESIGN OF EXPERIMENT 1

Experiment 1 consisted of three components, where each component addresses a specific set of research questions: 1) right-turning motorist's visual attention, 2) situational awareness (SA), and 3) crash avoidance behavior.

5.1.1 Factorial Design

Four independent variables were included in the experiment: relative position of bicyclist, bicyclist approach speed, oncoming left-turning vehicular traffic and, pedestrian presence in the conflicting crosswalk.

The first independent variable, "relative position of bicyclist," had three levels: 1) no bicyclists, 2) bicyclist approaching from behind the motorist, which placed the bicyclist in the blind spot to the right and behind the subject vehicle and 3) bicyclist riding ahead of the motorist where the motorist would overtake the bicyclist (overtaking scenario). When bicyclists were coded as approaching from behind the vehicle, they were introduced in the environment in the motorist's blind zone. This would represent a scenario where a bike turned onto the road from a driveway or was otherwise not initially observed by the driver. It maximized the potential effect between a turning motorist and the adjacent bicyclist.

The second independent variable, "bicyclist's speed," had two levels: 1) low (12 mph), and 2) high (16 mph). The third independent variable was the "presence of oncoming left-turning vehicular traffic", which had two levels – 1) no oncoming (zero) vehicles and 2) three oncoming vehicles.

The last factor was the "presence of a conflicting pedestrian in the crosswalk," which also had two levels: 1) no (zero) pedestrian and 2) one conflicting pedestrian walking towards the participant. Table 5.1 shows different experiment factors and their levels.

The factorial design resulted in 24 scenarios for inclusion in the experiment, which were manipulated within subjects. The within-subject design provides the advantage of greater statistical power and reduction in error variance associated with individual differences (Cobb 1998). However, one fundamental disadvantage of the within-subjects' design is "practice effects," which are caused by the participants' practice and growing experience as they move through the sequence of conditions. This effect is due to the participants' growing general familiarity with the procedures. To control for this effect, the order of the presentation of the scenarios to the participants need to be random ordered or counterbalanced.

Table 5.1: Experimental factors and levels.

Name of the Variable	Category	Levels
Bicyclist relative position	Nominal (Categorical)	None
		One (1) bicyclist riding in front of the motorist in an adjacent bicycle lane to the right
		One (1) bicyclist coming from behind the motorist in an adjacent bicycle lane to the right
Speed of bicyclist	Discrete	Low (12 mph)
		High (16 mph)
Presence of oncoming vehicular traffic	Dichotomous (Categorical)	None
		Three (3) Vehicles
Presence of conflicting pedestrian	Dichotomous (Categorical)	None
		One (1) pedestrian walking towards the motorist

5.1.2 Research Questions

The specific research questions associated with the assessment of the visual attention, SA, and crash avoidance behavior of motorists are presented in this sub-section.

5.1.2.1 Visual Attention

The visual attention of motorists was measured by eye-movement data collected with eye-tracker technology. Fisher et al. stated that eye-movement data provides direct evidence whether potential hazards are being anticipated in most cases *(Fisher et al. 2011).* As such, participants' eye-movement data were collected to investigate if they detect potential right-hook crash hazards (i.e., the through-moving bicyclist in the adjacent bicycle lane) before turning right at a signalized intersection. The potential influence of the experimental factors (Table 5.1) on a right-turning motorist's eye movement formed the basis of the research questions regarding the visual attention of motorists.

- *Research Question 1 (RQ_1)*: Is the visual attention of a right-turning motorist influenced by the relative position of the adjacent bicyclist?
- *Research Question 2 (RQ_2)*: Is the visual attention of a right-turning motorist influenced by a bicyclist's approaching speeds at a signalized intersection?
- *Research Question 3 (RQ_3)*: Is the visual attention of a right-turning motorist influenced by the presence of oncoming left-turning traffic at the intersection?
- *Research Question 4 (RQ_4)*: Is the visual attention of a right-turning motorist influenced by the presence of a conflicting pedestrian crossing the intersection?

Subsequently, research hypotheses were formulated to statistically analyze the eye-movement data of right-turning motorists. The research hypothesis, data analysis, and results for this set of experiments are detailed in "Chapter 7: Results: Experiment 1 Visual Attention."

5.1.2.2 Situational Awareness

Situational awareness can help to explain motorists' behavior by exploring several key factors: anticipation, attention, perception, expectations, and risk *(Endsley, 1998).* SA is the term given to the awareness that a person has of a situation, an operator's dynamic understanding of "what is going on" *(Endsley, 1995a).* Therefore, to analyze motorist-related crash factors, this experiment measured motorists' performance during right-turn maneuvers at signalized intersection in the presence of a through-moving bicyclist in an adjacent bicycle lane through their (i) visual attention, (ii) SA, and (iii) crash avoidance behavior.

The Situation Awareness Global Assessment Technique (SAGAT) *(Endsley, 1995)* was used to measure a right-turning motorist's SA in the presence of a through-moving bicyclist in an adjacent bicycle lane during the latter portion of the green phase at a signalized intersection. SAGAT is the most widely used measure of SA. It was developed and validated by Endsley *(1995)* to assess an operator's SA using queries for each of the three levels of SA proposed in the Endsley's three-level model. The three-level model is a cognitive theory that uses an information processing approach where the three levels are, level 1 SA (perception of the elements), level 2 SA (comprehension of their meaning), and level 3 SA (projection of future status) *(Endsley, 1995).* The research questions associated with SA were formulated to assess the influence of the relative position of bicyclists and the presence of oncoming left-turning traffic on motorists' SA while turning right during the latter portion of green phase at an intersection with bicycle traffic.

- *Research Question 5 (RQ_5)*: Does the relative position of a through-moving bicyclist in the adjacent bicycle lane influence right-turning motorists' SA at the latter portion of green phase at an intersection?

- *Research Question 6 (RQ_6)*: Does the presence of oncoming left-turning traffic influence right-turning motorists' SA at the latter portion of green phase at an intersection?

- *Research Question 7 (RQ_7)*: Do the combination of the presence of oncoming left-turning traffic and relative position of a bicyclist influence right-turning motorists' SA at the latter portion of green phase at an intersection?

- *Research Question 8 (RQ_8)*: Is there any correlation between the number of correct responses and crash avoidance behavior of a right-turning motorist in a driving simulator environment?

The research hypothesis, data analysis, and results for this set of experiments are detailed in "Chapter 8: Results: Experiment 1 Situational Awareness."

5.1.2.3 Crash Avoidance Behavior

Although situational awareness is key to decision making in a dynamic environment, it does not necessarily guarantee successful task performance *(Salmon et al. 2009).* Therefore, in addition to the explicit recall measures of SA, it is also important to assess an operator's SA with indirect performance-based measures *(Gugerty 1997).* In this experimental component, a motorist's performance was measured through the global performance measure of crash avoidance during right-turning maneuvers at the latter portion of the green indication and in the presence of bicyclists at a signalized intersection. Crash avoidance behavior helped to determine if a motorist was able to notice a bicyclist in a timely manner, decide to avoid the collision, and execute an evasive maneuver to ultimately avoid a right-hook crash at a simulated signalized intersection. The following research questions were established to guide the assessment of crash avoidance behavior:

- *Research Question 9 (RQ_9)*: What are the driving environment causal factors leading to the occurrence of a right-hook crash at the latter portion of a green phase observed in the simulated intersections?

- *Research Question 10 (RQ_{10})*: What are the human causal factors leading to the occurrence of a right-hook crash at the latter portion of a green phase observed in the simulated intersections?

The research hypothesis, data analysis, and results for this set of experiments are detailed in "Chapter 9: Results: Experiment 1 Crash Avoidance."

5.1.3 Road and Intersection Geometry

The cross section of the roadway included three 12-foot traffic lanes with 5.5-foot bicycle lanes in each direction. The intersection approaches included a single shared lane and a single receiving lane, whereas the opposing direction had two lanes. No exclusive left-turn or right-turn bay was provided at the intersection. The intersection approaches had a posted speed limit of 35 mph. Figure 5.1 shows an example of an intersection approach in the simulated environment as it was presented to the participants. This particular scenario includes the presence of oncoming left-turning vehicles waiting in the queue, and a bicyclist riding ahead of the right-turning motorist at the latter portion of green phase.

Figure 5.1: Screen capture of intersection approach in simulated environment.

5.1.4 Presentation of Driving Scenarios

The simulated environment was designed to put the motorist in situations where observations could be made to address specific research questions and hypotheses. For Experiment 1, 20 right-turning scenarios were presented to participants in the driving simulator experiment. Table 5.2 presents the layout of seven grids with 21 scenarios, where the crash-likely scenario is marked with asterisk (*) symbol. To measure the crash avoidance behavior of participants, they were exposed to a crash-likely scenario at the last intersection configuration. The worst possible combination of the four experimental factors (i.e., bicyclist approaching from the behind at 16 mph, three oncoming vehicles and one conflicting pedestrian) were presented in this crash-likely scenario. Therefore, in total 21 scenarios were included in this experiment.

The design and sequencing of the 21 scenarios was influenced by a need to minimize the occurrence of simulator sickness and to provide opportunities to freeze the simulation six times to measure motorists' SA. Therefore, the experimental driving was divided into seven individual grids of intersections, and the crash-likely scenario was presented at the last intersection of the seventh grid. The number of right-turning scenarios included in each grid was varied so that the simulation could be stopped at various intervals, a recommended best practice for measuring SA *(Endsley 1995b).* Each scenario was assigned a position on a grid based on the assignment of random number generation, except for the crash-likely scenario which had to appear last. The order of presentation of Grids 1 to 6 was counterbalanced to minimize the practice effect on driver performance. This arrangement also introduced “random nature” to the experiment, which helped to reduce the “practice effect” limitation of the within-subject design, and made it more difficult for participants to predict when the simulation would stop, which was necessary for the SA measurement.

Five grids consisted of three right-turning maneuvers, and the other two grids consisted of two or four right-turning maneuvers each. This distribution of 21 scenarios across seven grids provided participants with the opportunity to take small breaks between clusters of scenarios. Grids 1, 2, 4, 6 and 7 are comprised of three right-turning intersections. To provide more variability in the grid presentation, the start and finish locations of these grids were not consistent. Also, the right-turning scenarios were interrupted by through movements at intersections that were not experimental scenarios to prevent participants from anticipating the motivation for the study and to reduce simulator sickness.

Figure 5.2 shows an example of grid layout of three right-turning scenarios - Grid 1, 2 and 7. The “Path” in the Figure indicates the sequence of intersections participants were asked to drive through. The layout of other grids with two, three, and four right-turning scenarios are included in Appendix B.

Participants were given the instruction to turn right at an intersection through an automated voice command saying “*Turn Right at the Next Intersection.*” This voice command was automatically generated using a Java Script-based sensor placed at the right-turning intersection approach, which was triggered by the presence of the participant vehicle on the sensor.

Table 5.2: Experiment 1, grid and right-turning intersection layout.

RT #	Bicyclist Relative position	Oncoming Traffic	Bicyclist Speed (mph)	Crossing pedestrian
Grid 1				
1	1 bicyclist ahead	No vehicles	16	1 pedestrian towards the subject
2	1 bicyclist ahead	3 vehicles	12	1 pedestrian towards the subject
3	1 bicyclist behind	No vehicles	16	No pedestrian
Grid 2				
1	1 bicyclist behind	No vehicles	12	No pedestrian
2	1 bicyclist behind	No vehicles	16	1 pedestrian towards the subject
3	1 bicyclist ahead	3 vehicles	16	No pedestrian
Grid 3				
1	1 bicyclist ahead	No vehicles	12	1 pedestrian towards the subject
2	No bicyclists	No vehicles	N/A	1 pedestrian towards the subject
3	1 bicyclist ahead	3 vehicles	16	1 pedestrian towards the subject
4	1 bicyclist behind	3 vehicles	16	No pedestrian
Grid 4				
1	1 bicyclist ahead	No vehicles	12	No pedestrian
2	1 bicyclist behind	3 vehicles	16	1 pedestrian towards the subject
3	No bicyclists	No vehicles	N/A	No pedestrian
Grid 5				
1	1 bicyclist behind	3 vehicles	12	No pedestrian
2	No bicyclists	3 vehicles	N/A	No pedestrian
Grid 6				
1	1 bicyclist behind	No vehicles	12	1 pedestrian towards the subject
2	1 bicyclist behind	3 vehicles	12	1 pedestrian towards the subject
3	1 bicyclist ahead	No vehicles	16	No pedestrian
Grid 7				
1	No bicyclists	3 vehicles	N/A	1 pedestrian towards the subject
2	1 bicyclist ahead	3 vehicles	12	No pedestrian
3*	1 bicyclist behind	3 vehicles	16	1 pedestrian towards the subject

* Crash-likely scenario

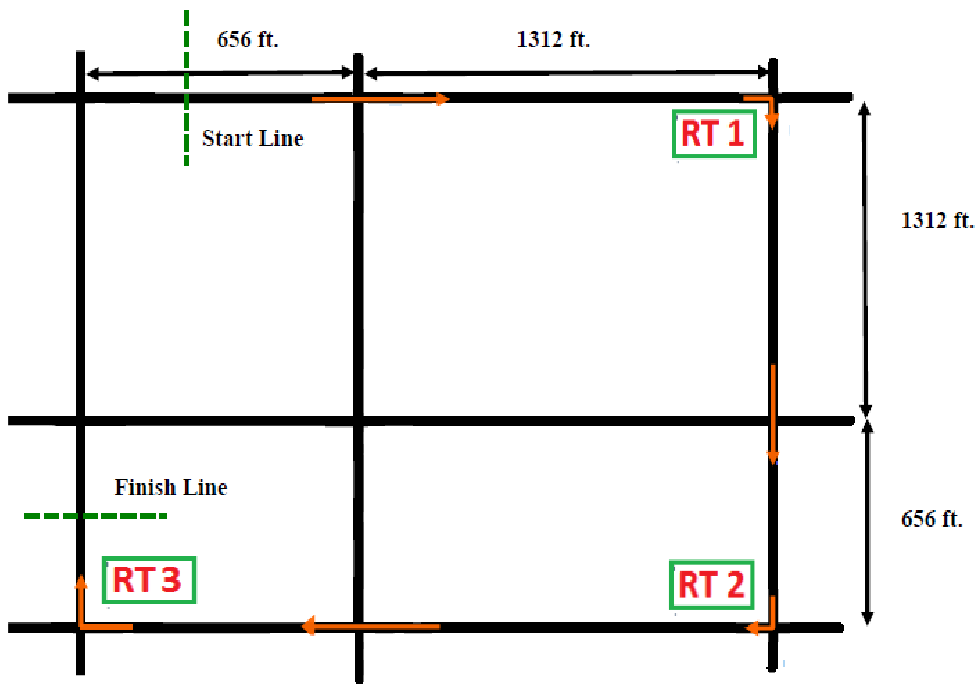


Figure 5.2: Example of grid layout of Grid 1, 2 and 7 with three right-turning (RT) scenarios – Path Start-Thru-Right-Thru-Right-Thru-Right-Finish.

5.1.5 Counterbalancing

To control for the practice or carryover effect, the order of the intersection grids were counterbalanced, (i.e., presented in random order). Randomized partial counterbalancing was chosen for this study due to the simplicity and flexibility it provided in terms of statistical analysis and number of required participants. In this randomized partial counterbalancing procedure, four different grid sequences were chosen depending on the two-, three- or four-intersection grid layout. The grid sequences were *6-3-4-2-5-1-7*, *2-3-1-6-5-4-7*, *1-2-3-5-4-6-7*, and *4-6-5-2-3-1-7*, which were randomly presented to the participants. Three of these grid sequences were randomly assigned 17 times and one sequence was randomly assigned 16 times to the 67 participants in this driving simulator study (Table 5.3).

Table 5.3: Random assignment of grid sequence to participants, experiment 1.

Grid Sequence	Frequency of presentation
6-3-4-2-5-1-7	17
2-3-1-6-5-4-7	17
1-2-3-5-4-6-7	16
4-6-5-2-3-1-7	17

5.2 DESIGN OF EXPERIMENT 2

Experiment 2 examined motorist behavior in response to four different categories of possible right-hook crash treatments. Right-turning motorists' visual attention and crash avoidance behavior, as well as potential crash severity were used to evaluate the relative performance of the alternative treatments. Additionally, a follow-up survey was used as an additional measure of relative performance between the treatments.

5.2.1 Factorial Design

The experiment included four independent variables (signage, pavement marking, curb radii, and protected intersections). Each independent variable was either dichotomous or categorical in nature and had either two, three, or four levels (Table 5.4). The factorial design resulted in 24 scenarios for inclusion in the experiment, in a fashion similar to Experiment 1. Figure 5.3 shows visual examples of the various treatment levels. While the signage, pavement marking, and curb radii treatments were fully counterbalanced between one another, the protected intersection was not counterbalanced against the pavement marking treatments, due to the physical design limitations of the protected intersection. It should also be noted that the protected intersection design used in the simulator was not intended to study constructability issues such as the truck turning/mountable curbs, reflective markings on curbs for visibility issues at night, issues about downhill grades, or accommodation of pedestrians.

Table 5.4: Experimental factors and levels.

Name of the Variable	Acronym	Category	Levels	Levels Descriptions
Signage	S	Dichotomous (Categorical)	0	None
			1	Signage
Pavement Marking	PM	Nominal (Categorical)	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 Radii	C	Discrete	0	Larger curb radii, 30^{ft}
			1	Smaller curb radii, 10^{ft}
Protected Intersection	PI	Nominal (Categorical)	0	None
			1	Protected intersection with islands
			2	Protected intersection with islands and green pavement markings

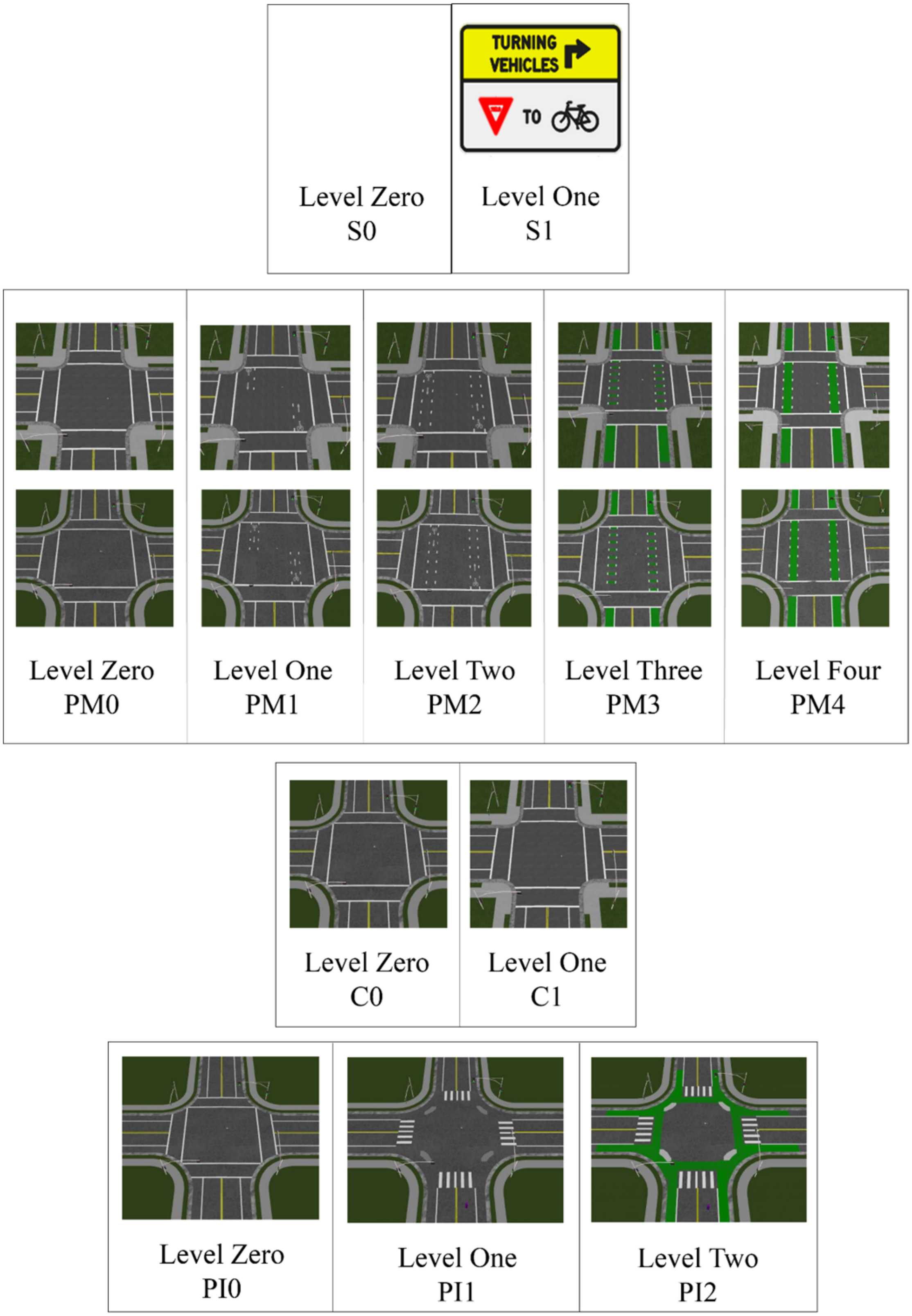


Figure 5.3: Experimental factors and levels.

5.2.2 **Research Questions**

The specific research questions associated with the assessment of the visual attention and crash avoidance behavior of motorists are presented in this sub-section.

5.2.2.1 Visual Attention

The visual attention of motorists was measured by eye-movement data, collected with eye-tracker technology, in a fashion consistent with Experiment 1. The potential influence of the experimental factors (Table 5.4) on right-turning motorists' eye movement formed the basis of the research questions regarding the visual attention of motorists.

- *Research Question 11 (RQ_{11})*: Is the visual attention of a right-turning motorist influenced by the signage?
- *Research Question 12 (RQ_{12})*: Is the visual attention of a right-turning motorist influenced by pavement markings?
- *Research Question 13 (RQ_{13})*: Is the visual attention of a right-turning motorist influenced by curb radii?
- *Research Question 14 (RQ_{14})*: Is the visual attention of a right-turning motorist influenced by protected intersection designs?

The research hypothesis, data analysis, and results for this set of experiments are detailed in "Chapter 11: Results: Experiment 2 Visual Attention."

5.2.2.2 Crash Avoidance Behavior

Motorist's performance was measured through the global performance measure of crash avoidance during right-turning maneuvers at the latter portion of the green indication and in the presence of bicyclists at a signalized intersection. Considering crash avoidance behavior for intersection approaches with different potential treatments helped to determine the relative impact of the alternative treatments. The following research questions were established to guide the assessment of crash avoidance behavior:

- *Research Question 15 (RQ_{15})*: Is the crash avoidance behavior of a right-turning motorist influenced by signage?
- *Research Question 16 (RQ_{16})*: Is the crash avoidance behavior of a right-turning motorist influenced by pavement markings?
- *Research Question 17 (RQ_{17})*: Is the crash avoidance behavior of a right-turning motorist influenced by curb radii?
- *Research Question 18 (RQ_{18})*: Is the crash avoidance behavior of a right-turning motorist influenced by protected intersection designs?

The research hypothesis, data analysis, and results for this set of experiments are detailed in "Chapter 12: Results: Experiment 2 Crash Avoidance."

5.2.2.3 Potential Crash Severity

The potential crash severity of incidents was measured by motorist vehicle velocities, collected with the driving simulator. Higher velocities at the time of the traffic conflict are considered to be more severe, as injuries to the cyclist generally increase with higher velocities. Considering vehicle velocities for intersection approaches with different potential treatments helped to determine the relative impact of the alternative treatments. The following research question were established to guide the assessment of crash severity:

- *Research Question 19 (RQ_{19})*: Is the potential crash severity of a right-hook crash during the latter portion of a green phase influenced by signage?
- *Research Question 20 (RQ_{20})*: Is the potential crash severity of a right-hook crash during the latter portion of a green phase influenced by pavement markings?
- *Research Question 21 (RQ_{21})*: Is the potential crash severity of a right-hook crash during the latter portion of a green phase influenced by curb radii?
- *Research Question 22 (RQ_{22})*: Is the potential crash severity of a right-hook crash during the latter portion of a green phase influenced by protected intersection designs?

The research hypothesis, data analysis, and results for this set of experiments are detailed in "Chapter 13: Results: Experiment 2 Crash Severity."

5.2.3 Road and Intersection Geometry

The cross section of the roadway included three 12-foot traffic lanes with 6-foot bicycle lanes in each direction. The intersection approaches included a single shared lane and a single receiving lane. The intersection approaches had a posted speed limit of 35 mph. Figure 5.4 shows an example of an intersection approach in the simulated environment as it was presented to the participants. This particular example shows the case where the motorist has yielded for the bicyclist.

Figure 5.4: Screen capture of an Experiment 2 intersection approach in simulated environment.

5.2.4 **Presentation of Driving Scenarios**

For Experiment2, 24 right-turning scenarios were presented to participants across six grids, shown in Table 5.5. To measure the influence of treatment alternatives, participants were exposed to a variety of different treatment configurations. The design and sequencing of the 24 scenarios was selected based on similar logic to that of Experiment 1. It is important to note that due to a coding error, two of the 24 scenarios were duplicated and not fully counterbalanced (number 21 duplicated in 23 and number 22 duplicated 24). These are the four scenarios related to the protected intersection treatment. This duplication was taken into consideration during the analysis of the resulting data.

Figure 5.5 shows an example of grid layout of four right-turning scenarios – Grid 5. The "Path" in the Figure indicates the sequence of intersections participants were asked to drive through. The layout of other grids with two, three, and four right-turning scenarios are included in Appendix C.

Participants were given the instruction to turn right at an intersection through an automated voice command saying "*Turn Right at the Next Intersection.*" This voice command was automatically generated using a Java Script-based sensor placed at the right-turning intersection approach, which was triggered by the presence of the participant vehicle on the sensor.

Table 5.5: Experiment 2, grid and right-turning intersection layout.

T #	RT #	Signage	Pavement Marking	Curb Radii	Protected Intersection
Grid 1					
11	1	Turning veh yield	None	30 ft.	None
23	2	None	None	30 ft.	Protected intersection w/islands
3	3	None	Double dotted white lane lines with stencil	30 ft.	None
20	4	Turning veh yield	Full green bike lane with dotted white outline	30 ft.	None
Grid 2					
17	1	Turning veh yield	Single dotted white bike lane line with stencil	10 ft.	None
22	2	Turning veh yield	None	30 ft.	Protected intersection w/ islands and green pavement
13	3	Turning veh yield	Double dotted white lane lines with stencil	30 ft.	None
7	4	None	Single dotted white bike lane line with stencil	10 ft.	None
Grid 3					
8	1	None	Double dotted white lane lines with stencil	30 ft.	None
14	2	Turning veh yield	Skipped green bike lanes with white outline	30 ft.	None
5	3	None	Full green bike lane with dotted white outline	30 ft.	None
16	4	Turning veh yield	None	10 ft.	None
Grid 4					
19	1	Turning veh yield	Dotted green bike lanes with white outline	10 ft.	None
15	2	Turning veh yield	Full green bike lane with dotted white outline	30 ft.	None
1	3	None	None	30 ft.	None
4	4	None	Skipped green bike lanes with white outline	30 ft.	None
Grid 5					
10	1	None	Full green bike lane with dotted white outline	10 ft.	None
2	2	None	Single dotted white bike lane line with stencil	30 ft.	None
21	3	None	None	30 ft.	Protected intersection w/islands
9	4	None	Skipped green bike lanes with white outline	10 ft.	None
Grid 6					
12	1	Turning veh yield	Single dotted white bike lane line with stencil	30 ft.	None
24	2	Turning veh yield	None	30 ft.	Protected intersection w/ islands and green pavement
6	3	None	None	10 ft.	None
18	4	Turning veh yield	Double dotted white lane lines with stencil	10 ft.	None

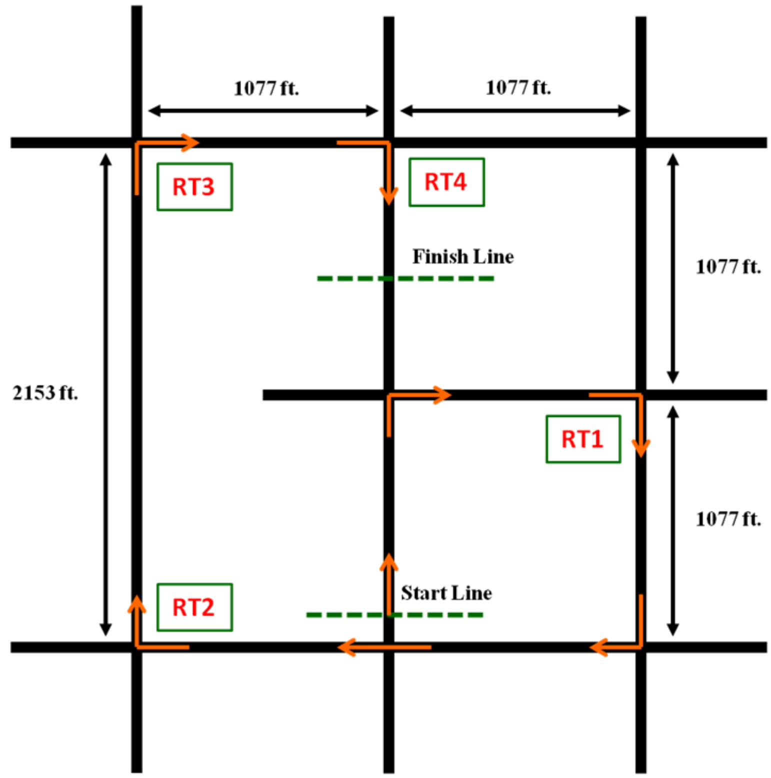


Figure 5.5: Example of Experiment 2 grid layout with four right-turning (RT) scenarios – Grid 5 Path: Start-Right-Right-Right-Thru-Right-Right-Right-Finish.

5.2.5 Counterbalancing

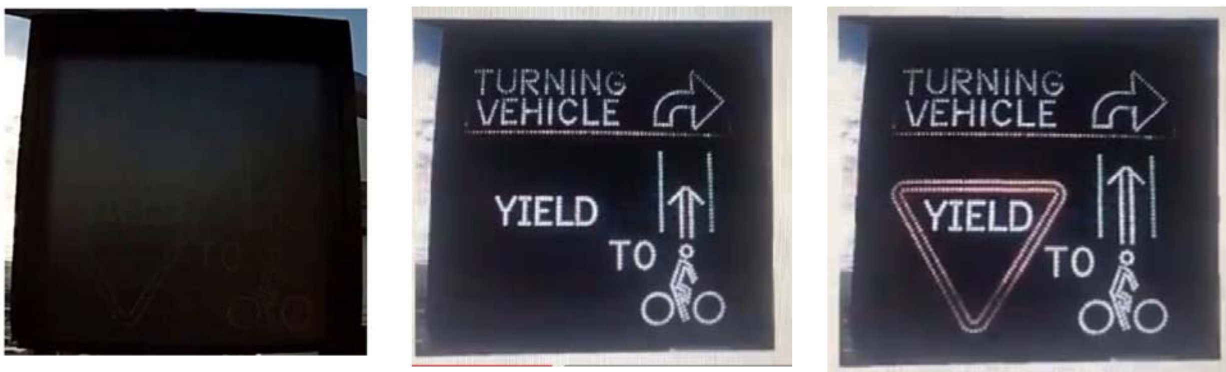
To control for the practice or carryover effect, the order of the intersection grids were counterbalanced, in a process similar to Experiment 1. In this randomized partial counterbalancing procedure, six different grid sequences were chosen. The grid sequences were 1-2-4-3-5-6, 2-4-5-1-3-6, 4-2-5-3-6-1, 5-2-3-6-1-4, 5-6-1-4-2-3, and 6-3-1-5-4-2 which were randomly presented to the participants. The frequency with which these sequences were assigned is detailed in Table 5.6.

Table 5.6: Random assignment of grid sequence to participants, experiment 2.

Grid Sequence	Frequency of presentation
124356	5
245136	3
425361	5
523614	4
561423	9
631542	2

5.2.6 **Follow-up Survey**

A follow-up survey was administered after the driving simulator portion of Experiment 2. The response data were collected with online Qualtrics survey software. The survey was used to determine motorist perceptions of the selected engineering treatments and their visual attention, with respect to an adjacent bicyclist. Additionally, the survey was used to determine motorist perceptions of a treatment that was unable to be tested within the simulated environment: the dynamic “Turning Vehicle Yield to Bikes” traffic sign currently implemented in Portland, OR, Participants were shown a video of the sign activating and it’s dynamic message which are shown in Figure 5.6.



a.) sign dark

b) sign activated

c) flashing yield triangle and arrow growing bottom to top

Figure 5.6: Sequence of phases of the dynamic “Turning Vehicle Yield to Bikes” sign.

6.0 PARTICIPANTS

This chapter summarizes the basic profile and demographics of the subjects used in the simulator studies. Data from both experiments are presented in this chapter.

6.1 SUMMARY STATISTICS

For Experiment 1, 67 participants (35 male and 32 female) participated in the simulator study. Approximately 24% (11 female and five male) of participants reported simulator sickness at various stages of the experiment (Table 6.1). All responses recorded from the participants who exhibited simulator sickness were excluded from the original data set. Thus, the final data set was comprised of 51 participants: 30 male (45 % of total) and 21 female (31 % of total) (Table 6.1). In Experiment 2, 46 participants were recruited. A higher rate of simulator sickness was observed (39%). Thus the final data set consisted of 18 male and 10 female drivers. Table 6.2 demonstrates the participants' demographics of this simulator experiment.

Table 6.1: Summary of participant population.

Categories	Experiment 1			Experiment 2		
	Total	Male	Female	Total	Male	Female
Total	67 (100%)	35 (52%)	32 (48%)	46 (100%)	26 (57%)	20 (43%)
Sim Sick (%)	16 (24%)	5(7%)	11(16%)	18 (39%)	7 (15%)	10 (22%)
Participated (%)	51 (76%)	30 (45%)	21(31%)	28 (61%)	18 (39%)	10 (22%)

6.2 DEMOGRAPHICS

Every effort was made to recruit a representative sample of the driving public (see Section 4.2.1). Table 6.2 shows the summary demographic data for the participants in both experiments. All participants were licensed drivers who reside in the state of Oregon (not necessarily Oregon licensed).

Table 6.2: Participant demographics.

		Experiment 1		Experiment 2	
Category	**Possible Responses**	**Number of Participants**	**Percentage of Participants**	**Number of Participants**	**Percentage of Participants**
What is your highest completed level of education?	High School Diploma	2	4 %	1	4%
	Some College	17	33 %	13	46%
	Associates Degree	6	12 %	0	0%
	4-year Degree	13	25 %	10	36%
	Master's Degree	11	22 %	3	11%
	PhD Degree	2	4 %	0	0%
	Other	0	0 %	1	4%
How many years have you been licensed?	1 - 5 years	19	37%	13	46%
	6 - 10 years	14	27 %	4	14%
	11 - 15 years	4	8 %	0	0%
	16 - 20 years	2	4%	2	7%
	More than 20 years	12	24 %	9	32%
What corrective lenses do you wear while driving?	Glasses	0	0 %	2	7%
	Contacts	13	25 %	10	36%
	None	38	75%	16	57%
Do you experience motion sickness?	Yes	6	12 %	4	14%
	No	45	88 %	24	86%
Gender	Male	30	59 %	18	64%
	Female	21	41 %	10	36%
Age	Minimum	Average	Maximum	Average	Maximum
	19	30.24	69	38.04	70

7.0 RESULTS: EXPERIMENT 1 VISUAL ATTENTION

This chapter summarizes the analysis of the participant's eye-tracking data, which were collected with an eye tracker with head-mounted optics while driving in 20 typical right-turning intersections in the simulated environment. The chapter describes in more detail the experimental hypothesis for the visual attention component of the evaluation for Experiment 1.

7.1 DESCRIPTION OF EXPERIMENT

One of the common features of BMV crashes at intersections include motorists' learned routine of failing to account for an adjacent bicyclist before turning *(Räsänen and Summala 1998).* We hypothesized that right-turning motorists' visual search will be influenced by the relative position of bicyclists. We inferred that motorists would fail to detect the bicyclist when approaching from behind in the motorist's blind spot as compared to when the bicyclist is riding in front of the motorist in his focal vision. Two hypotheses were formulated:

- $H_{0\,(VSP1)}$: Relative positions of adjacent bicyclists have no effect on the right-turning motorists' mean total fixation duration on areas of interest in the driving environment.

- $H_{0\,(VSP2)}$: There is no difference in the proportion of motorists who fixate on an adjacent bicyclist during the right-turn maneuver at signalized intersections as the relative position of the bicyclist changes.

It has also been suggested that before turning right, motorists tend to focus their attention on the cars coming from the left, and fail to notice bicycles coming from their right early enough to respond safely *(Summala et al. 1996).* Therefore, we hypothesized that motorists' visual attention will be influenced when an oncoming car turns left in front of the motorist. Also, an investigation of crashes at bike boxes by the Portland Bureau of Transportation suggested that the speed of bicyclists overtaking the right-turning vehicle was a contributing factor to the occurrence of right-hook crashes *(Bureau of Transportation 2012).* We inferred that a bicyclist's speed would have an effect on the visual attention of motorists while turning right during the latter portion of the green phase. The Institute of Transportation Engineers (ITE) *Transportation Planning Handbook* states that one of the most common pedestrian crashes is the vehicle turn/merge conflict type *(Meyer 2009).* This conflict type occurs when a pedestrian and vehicle collide while the vehicle is conducting, preparing, or has just completed a turning movement *(Hurwitz et al. 2013).* Thus we also hypothesized that the presence of a pedestrian in the conflicting crosswalk might influence the visual attention of a right-turning motorist. Three additional hypotheses were formulated:

- $H_{0\,(VSP3)}$: The speed of adjacent bicyclists has no effect on right-turning motorists' mean total fixation duration on areas of interest in the driving environment.

- $H_{0\ (VSP4)}$: The presence of oncoming left-turning vehicular traffic has no effect on the right-turning motorists' mean total fixation duration on areas of interest in the driving environment.

- $H_{0\ (VSP5)}$: The presence of a pedestrian in the conflicting crosswalk has no effect on the right-turning motorists' mean total fixation duration on areas of interest in the driving environment.

7.2 DESCRIPTIVE DATA ANALYSIS

Fifty-one participants successfully completed the Experiment 1 driving simulator experiment. However, due to the eye-tracker calibration issues, completely usable data was collected for 41 participants. This represents a total of 820 (41*20) right-turn maneuvers. These data were reduced as described in prior section. Figure 7.1 presents an annotated illustration of the AOIs that were explored in the analysis of visual attention. Table 7.1 summarizes the average total fixation durations (ATFDs) of each AOI collected at the 20 right-turn experimental scenarios.

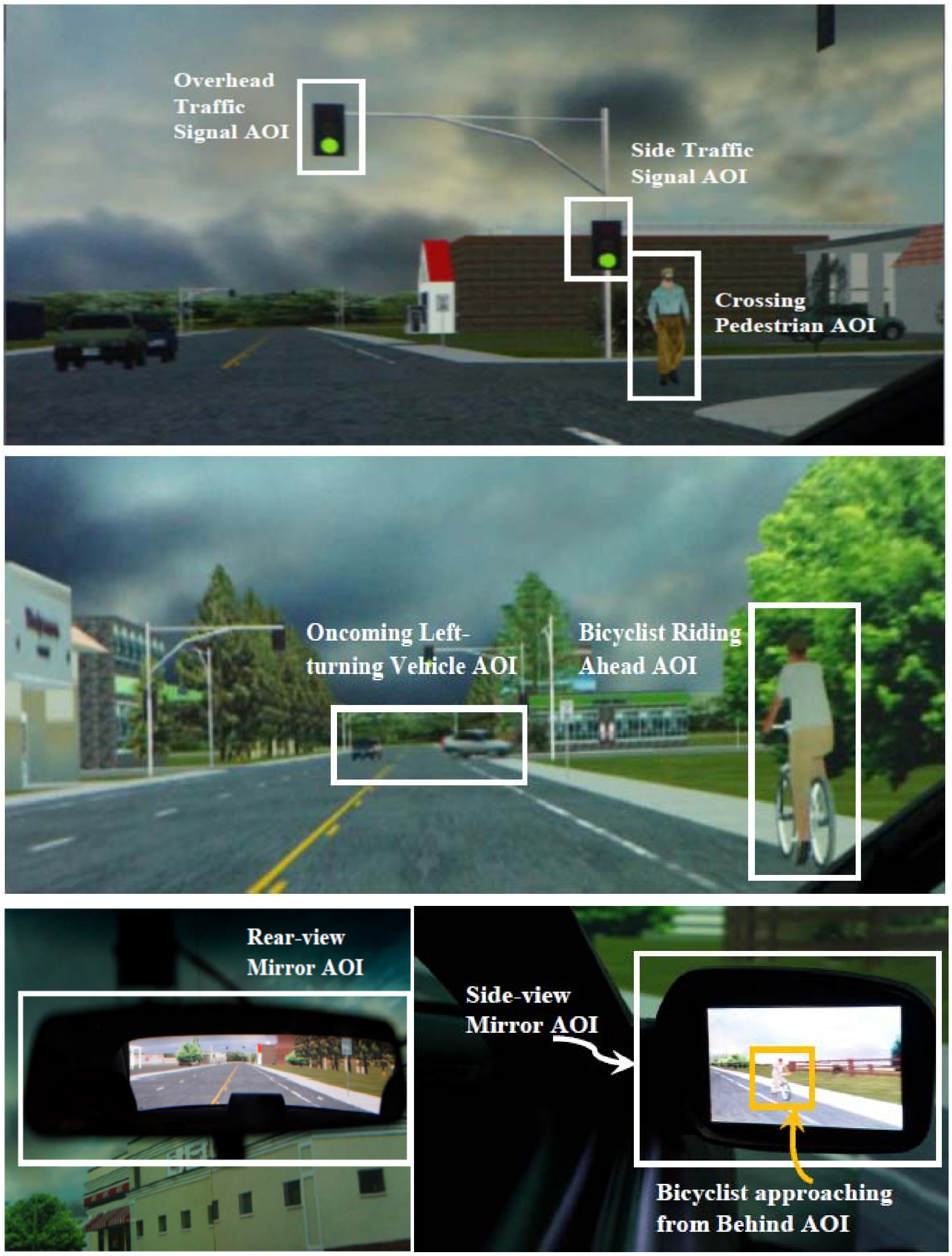


Figure 7.1: Examples of different AOIs motorists fixated on during the experiment.

Table 7.1: Summary of AOI Average Total Fixation Durations (AFTD, secs) by scenario.

Scenario	Intersection Information				ATFD (sec)							
	Bicyclist Relative Position	Oncoming Vehicle	Bicyclist Speed (mph)	Crossing pedestrian	Ped	Bicyclist Ahead	Bicyclist Behind	Signal Overhead	Signal Side	RV Mirror	Side Mirror	Oncoming veh
Grid 1_1	Bicyclist ahead	No veh	16	1 ped	4.54	1.51	-	0.09	0.21	0.31	0.42	-
Grid 1_2	Bicyclist ahead	3 veh	12	1 ped	3.24	1.20	-	0.19	0.21	0.61	0.55	1.29
Grid 1_3	Bicyclist behind	No veh	16	No ped	-	-	0.06	0.09	0.12	0.32	0.58	-
Grid 2_1	Bicyclist behind	No veh	12	No ped	-	-	0.19	0.12	0.13	0.38	0.52	-
Grid 2_2	Bicyclist behind	No veh	16	1 ped	4.24	-	0.34	0.12	0.27	0.70	0.50	-
Grid 2_3	Bicyclist ahead	3 veh	16	No ped	-	1.34	-	0.25	0.12	0.28	0.29	1.97
Grid 3_1	Bicyclist ahead	No veh	12	1 ped	3.34	1.80	-	0.12	0.16	0.57	0.40	-
Grid 3_2	No bicyclist	No veh	N/A	1 ped	4.61	-	-	0.11	0.28	0.57	0.32	-
Grid 3_3	Bicyclist ahead	3 veh	16	1 ped	1.99	1.06	-	0.10	0.10	0.27	0.26	1.33
Grid 3_4	Bicyclist behind	3 veh	16	No ped	-	-	0.08	0.19	0.04	0.34	0.30	1.98
Grid 4_1	Bicyclist ahead	No veh	12	No ped	-	1.37	-	0.08	0.12	0.56	0.37	-
Grid 4_2	Bicyclist behind	3 veh	16	1 ped	3.69	-	0.32	0.23	0.11	0.34	0.46	2.26
Grid 4_3	No bicyclist	No veh	N/A	No ped	-	-	-	0.43	0.09	0.42	0.23	-
Grid 5_1	Bicyclist behind	3 veh	12	No ped	-	-	0.16	0.21	0.10	0.31	0.57	1.79
Grid 5_2	No bicyclist	3 veh	N/A	No ped	-	-	-	0.08	0.07	0.25	0.19	1.52
Grid 6_1	Bicyclist behind	No veh	12	1 ped	4.58	-	0.57	0.21	0.10	0.40	0.39	-
Grid 6_2	Bicyclist behind	3 veh	12	1 ped	3.56	-	0.28	0.10	0.15	0.42	0.30	2.01
Grid 6_3	Bicyclist ahead	No veh	16	No ped	-	1.75	-	0.06	0.12	0.34	0.27	-
Grid 7_1	No bicyclist	3 veh	N/A	1 ped	3.08	-	-	0.12	0.11	0.48	0.43	1.44
Grid 7_2	Bicyclist ahead	3 veh	12	No ped	-	1.16	-	0.11	0.10	0.53	0.56	1.07

Note: "-" in table means AOI not presented in that grid.

Figure 7.2 shows the ATFD values and 95% confidence intervals (CIs) for four AOIs at an intersection scenario where the motorist was presented with no pedestrians, no oncoming vehicles, and no bicyclists. This particular intersection is the most basic of all intersections shown to the participants. Note that the AFTDs are all below 0.50 seconds.

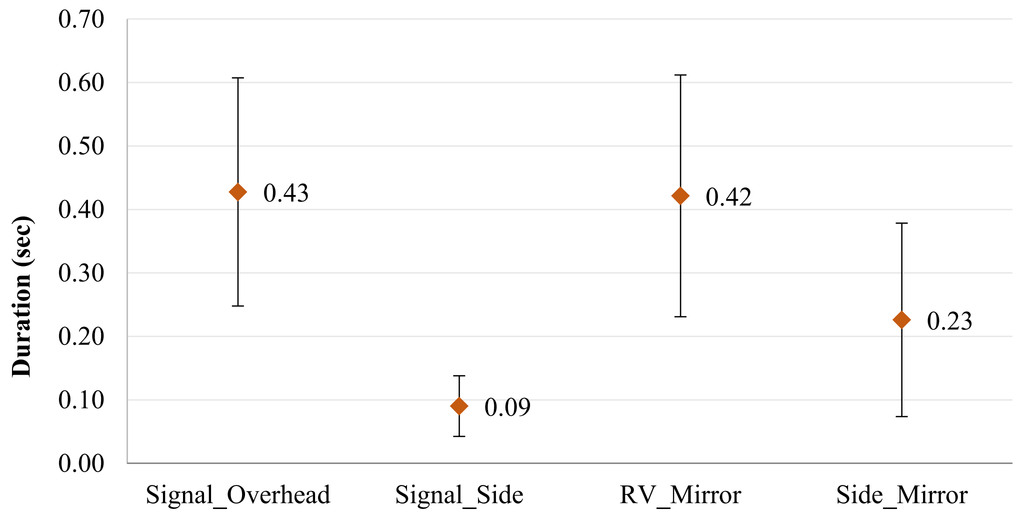


Figure 7.2: ATFDs with 95% CIs for control case (no bicyclists, no vehicles, and no pedestrians).

Figure 7.3 shows the ATFDs from all participants at an intersection where the bicyclist was approaching from behind the motorist at 16 mph, oncoming vehicles were present, and a pedestrian was present in the conflicting crosswalk. This case includes the greatest number of experimental variables, and is one of the most visually complex scenarios.

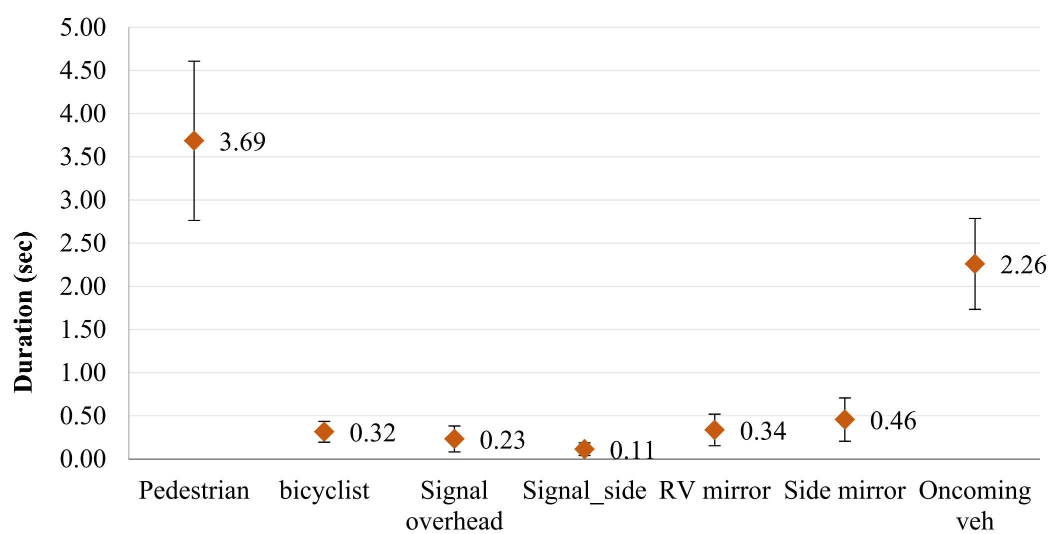


Figure 7.3: ATFD with 95% CIs for one of the most visually complex scenario (bicyclist approaching from behind at 16 mph, three vehicles, one conflicting pedestrian).

Figure 7.4 represents the ATFDs from all participants for the other most visually complex scenarios where the bicyclist was riding **ahead** of the motorist at 16 mph, oncoming vehicles were present, and a pedestrian was present in the conflicting crosswalk. Appendix D contains plots of all ATFDs and 95% CIs for all 20 experimental scenarios.

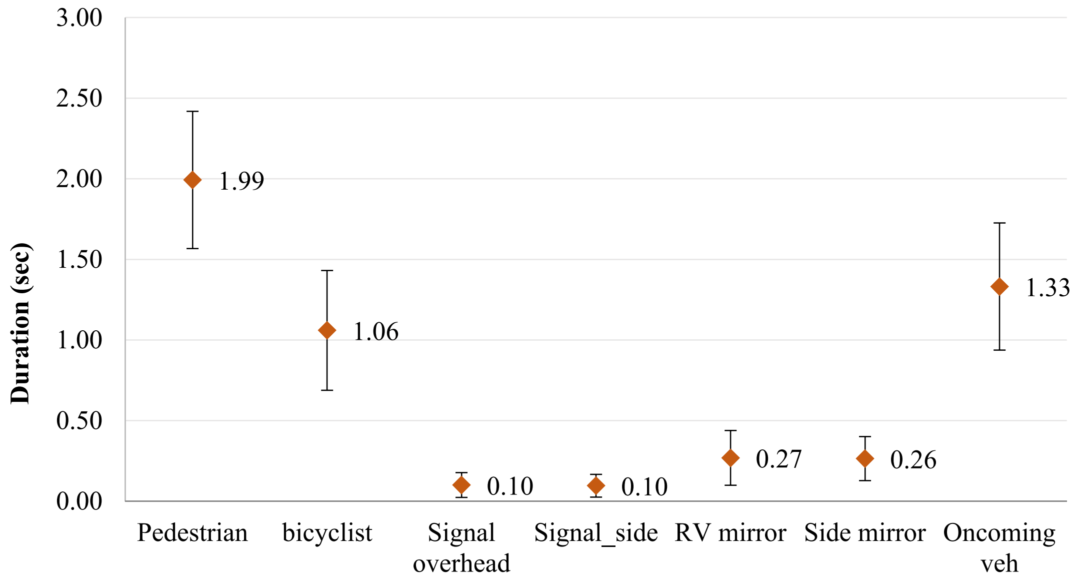
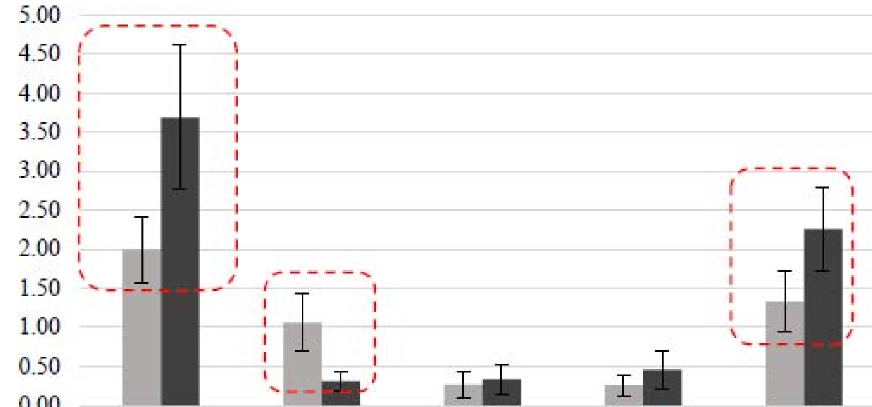


Figure 7.4: ATFD with 95% CIs for the other most visually complex scenario (bicyclist riding in the front at 16 mph, three vehicles, one conflicting pedestrian).

Figure 7.5 shows the ATFDs of five AOIs for two experimental scenarios in which all factors were kept constant (one pedestrian crossing the intersection and three oncoming vehicles) except for the relative position of bicyclists (ahead vs behind) riding at 16 mph. As described in Chapter 6, Grid 3-3 represents the intersection where the bicyclist was riding in front of the motorist at 16 mph, whereas Grid 4-2 represents the intersection where the bicyclist was approaching from behind the motorist at 16 mph. The graphical comparison shows that the 95% CIs of the ATFDs for the bicyclist's position, crossing pedestrian, and the oncoming vehicle do not overlap with respect to different bicyclist position. This finding suggests that when a bicyclist is in the motorist's blind zone (behind), right-turning motorist spends less time (0.32 sec) scanning for the bicyclist as compared to when the bicyclist is riding at the motorist's forward field of view (1.06 sec). A two-sample Welch's *t*-test (determined by Levene's Homogeneity of Variance test) resulted in a two-tailed p-value of less than 0.001 for this comparison. The graphical comparison also shows that when a bicyclist was riding in the motorist's forward field of view, the motorist spend less time fixating on the pedestrian (1.99 sec vs 3.69 sec) and oncoming vehicles (1.33 sec vs 2.26 sec) compared to when the bicyclist was riding behind. Two-sample Welch's *t*-tests (determined by Levene's Homogeneity of Variance test) resulted in two-tailed p-values of less than 0.001 and 0.007 for these comparisons, respectively.



	Pedestrian	Bicyclist	RV mirror	Side mirror	Oncoming veh
Grid 3-3 (Bike Ahead)	1.99	1.06	0.27	0.26	1.33
Grid 4-2 (Bike Behind)	3.69	0.32	0.34	0.46	2.26

Figure 7.5: Bar plots of ATFD (s) for two similar intersections with different bicyclist positions.

7.3 STATISTICAL ANALYSIS

The relative position and speed of bicyclists, presence of oncoming left-turning vehicular traffic, and conflicting pedestrian in the crosswalk may influence motorists' visual attention while turning right. Therefore, all these factors were included as independent variables. It should be noted that although other factors (for example, motorists' experience level, age or conspicuity of the bicyclist) may also influence motorists' visual search task at an intersection; those factors are outside the scope of this study. The first independent variable, "relative position of bicyclist," had three levels: 1) no bicyclists, 2) bicyclist approaching from behind the motorist, and 3) bicyclist riding ahead of the motorist. The second independent variable, "bicyclist's speed," had two levels: 1) low (12 mph), and 2) high (16 mph). The third independent variable was the "presence of oncoming left-turning vehicular traffic," which had two levels: 1) no oncoming (zero) vehicles and 2) three oncoming vehicles. The last independent variable was the "presence of a conflicting pedestrian in the crosswalk," which also had two levels: 1) no (zero) pedestrian and 2) one conflicting pedestrian walking towards the participant.

The primary dependent variable of this experiment was the visual attention of motorists during the right-turn maneuver at signalized intersections. Average total fixation duration (ATFD) was documented for each Area of Interest (AOI) as it provided a quantitative measure of how motorist visual attention was distributed across targets (Fisher et al., 2011). Fixation data for different AOIs were statistically analyzed to answer the research hypotheses using SPSS (IBM SPSS Statistics, V22.0).

7.3.1 Relative Position of Bicyclist

To answer the first research hypothesis ($H_{0\ (VSP1)}$) regarding the relative position of the bicyclist with respect to the motorist, the dataset was split by the three levels of bicyclist position: 1) bicyclist riding in the front, 2) bicyclist approaching from the behind, and 3) no bicyclist.

The first two levels were included in eight experimental scenarios each and the third level resulted in four experimental scenarios. The dataset was aggregated this way to isolate the impact of individual variable levels. Figure 7.6 shows the ATFDs with 95% CIs on AOI by bicyclist position.

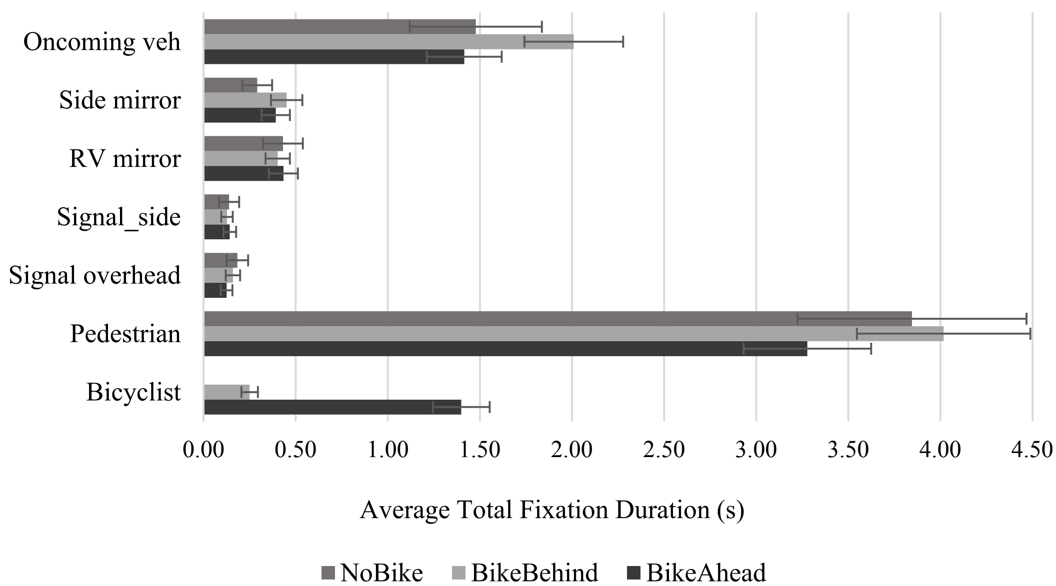


Figure 7.6: Bar plot of ATFDs at all intersections by bicyclist position.

Analysis of variance (ANOVA) was used to statistically determine if there is any difference in the ATFDs with respect to bicyclist's position. However, when the variances were not equal (determined by Levene's test), indicating the violation of the assumption of homogeneity of variance, the Welch's Robust test or Omnibus F were used to interpret the *F*-statistic. Finally, pairwise comparisons were calculated with Tukey's Honest Significant Difference (HSD) test. Table 7.2 presents the results of these tests, with statistically significant p-values shown in bold.

Table 7.2: ANOVA analysis of difference in ATFDs by bicyclist position.

Area of Interest	**Relative position of bicyclist**			**ANOVA**	**Tukey's HSD for pairwise comparisons of means w.r.t bicyclist positions**								
	Ahead	Behind	None	All	Ahead vs Behind			Ahead vs None			Behind vs None		
	ATFD			p-value	p-value	Sig	Diff	p-value	Sig	Diff	p-value	Sig	Diff
Bicyclist	1.40	0.25	N/A	N/A	<0.001 †	Yes	1.15	N/A			N/A		
Pedestrian	3.28	4.02	3.85	**0.03 ***	0.039	Yes	-0.74	0.28	No	-0.57	0.89	No	0.17
Signal overhead	0.13	0.16	0.18	**0.16 ***	0.4	No	-0.03	0.17	No	-0.06	0.74	No	-0.02
Signal_side	0.14	0.13	0.14	0.83	0.82	No	0.014	0.99	No	0	0.95	No	-0.01
RV mirror	0.43	0.40	0.43	0.82	0.83	No	0.03	0.99	No	0	0.9	No	-0.03
Side mirror	0.39	0.45	0.29	**0.03***	0.53	No	-0.06	0.302	No	0.1	0.049	Yes	0.16
Oncoming veh	1.42	2.01	1.48	**0.002 ***	0.002	Yes	-0.59	0.95	No	-0.06	0.53	No	-0.03

† No multiple comparisons required. P-value reflects a two-sided Welch's two sample *t*-test
* P-value reflects a Welch *F* test

The ANOVA analysis showed that fixations on the bicyclist, pedestrian, right-side mirror, and oncoming vehicles had statistically significant differences as measured by ATFDs. A two-sided Welch's two sample *t*-test indicated a statistically significant difference in the ATFDs on bicyclists with respect to bicyclists' position. It revealed that motorists spent more time fixating on the bicyclist when it was riding in the forward field of view as compared to when the bicyclist was approaching from behind the motorist. The ATFD for the pedestrian AOIs was different when a bicyclist was riding in the front vs when the bicyclist was approaching from the behind. This finding revealed that in the presence of a bicyclist in the forward field of view, motorists spent less time fixating on the pedestrian compared to when the bicyclist was approaching from the behind. Similar findings were observed in the case of the oncoming vehicle AOI. However, a statistically significant difference in the ATFDs on the right-side mirror and corresponding pairwise comparison showed that motorists spent more time fixating on the right-side mirror when a bicyclist was approaching from behind compared to when there was no bicyclist present at the intersection. No other significant differences were found with 95% confidence.

7.3.2 Motorists Not Fixating on Bicyclist

In addition to the assessment of the ATFDs on the bicyclist with respect to different bicyclist positions, another research interest ($H_{0\,(VSP2)}$) was to investigate the percentage of motorists who fixated on the bicyclist before turning right at an intersection. Individual motorist fixation behavior was examined for two different bicyclist positions (approaching the intersection in front of or behind the motorist) for this purpose. Since the target where the eyes are pointing is a good indication of what is being processed *(Fisher et al., 2011),* a fixation on a bicyclist will likely indicate if he was scanned or detected by the motorist during a right-turn maneuver. Therefore, the determination of the detection of a bicyclist was limited to when a motorist fixated directly on the bicyclist. For example, a motorist who fixated on the RV or side mirror, but did not fixate on the bicyclist coming from behind and afterwards turned-right without yielding to the bicyclist

- these cases indicated that the motorist failed to detect the bicyclist and were coded as “not fixated” in the analysis.

As depicted in Table 7.3, there were 328 (41 participants*8 turns) right-turn scenarios for each bicyclist position. When the bicyclist was riding ahead of the motorist in his forward field of view, in 87% of the cases the motorists fixated on the bicyclist (i.e., actively scanned for the bicyclist before turning right). However, when a bicyclist was approaching from behind in the motorist’s blind zone, in only 44% of the scenarios did a motorist fixate on the bicyclist before turning right. A Chi-square test revealed a statistically significant difference (p-value < 0.001) between the frequencies of motorist fixation on the bicyclist with different bicyclist positions.

Table 7.3: Frequency of motorist fixation on bicyclist before turning right.

Frequency of fixation	Bicyclist position	
	Ahead	Behind
Total (n)	328	328
Fixated	284	145
%	87%	44%

7.3.3 Speed of Adjacent Bicyclist

A comparison of all ATFDs with respect to the bicyclist’s speed in the adjacent bike lane was also conducted. To address $H_{0\,(VSP3)}$, the dataset was divided by the two levels of bicyclist speed of 16 mph and 12 mph. These two groups consisted of eight experimental scenarios each. Figure 7.7 shows the ATFDs with 95% CIs on AOIs by bicyclists’ speed.

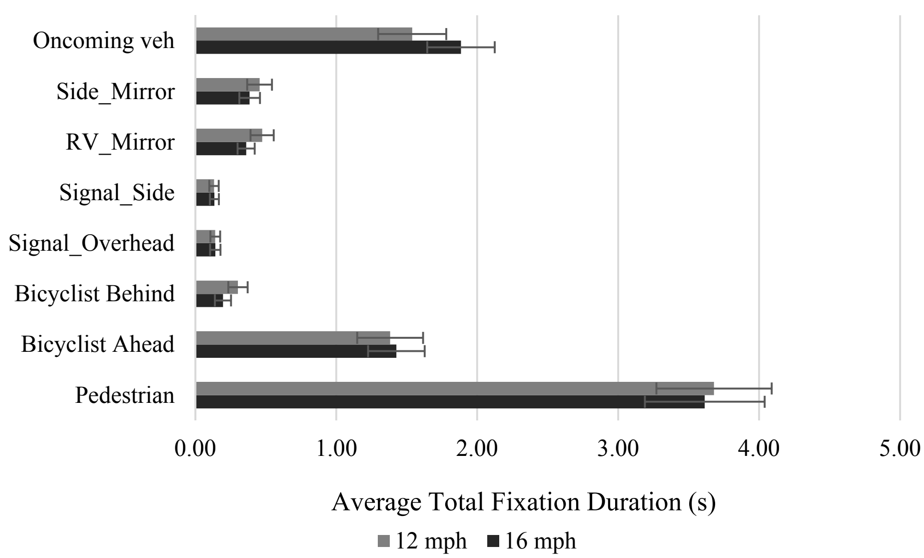


Figure 7.7: Bar plot of ATFDs at all intersections, according to bicyclist’s speed.

Table 7.4 presents the results of a two-sample, two-sided t-test that was conducted to determine the difference in the ATFDs with respect to bicyclists’ speed. As stated before, when the variances were not equal (determined by Levene's test), indicating the violation of the assumption of homogeneity of variance, the Welch's t-test were used. A statistically significant difference was found in the ATFDs on the rearview mirror AOI with changes in the bicyclist's speed. When the bicyclist's speed was lower (12 mph), motorists spent more time scanning the rearview mirror compared to higher (16 mph) speed scenarios. This was likely because the bicyclist required more time to travel the same distance before reaching the intersection at lower speed compared to higher speed, while the motorist yielded for him to pass. Since the motorist had to wait longer for the bicyclist to pass at the lower speed, the time spent fixating on the rearview mirror searching for bicyclist was greater than when the bicyclist was at higher speed.

Table 7.4: Two-sample *t*-test of ATFDs by bicyclist speed.

Areas of Interest	Speed of Bicyclist		Two sample two tail *t*-test	
	16 mph	12 mph	*16 mph vs 12 mph*	
	ATFD (sec)		p-value	Significant
Pedestrian	3.61	3.68	0.83	No
Bicyclist Ahead	1.43	1.38	0.78	No
Bicyclist Behind	0.20	0.30	0.98	No
Signal_Overhead	0.14	0.14	1.00	No
Signal_Side	0.14	0.13	0.91	No
RV_Mirror	0.36	0.47	0.03 †	Yes
Side_Mirror	0.39	0.46	0.23 †	No
Oncoming veh	1.89	1.54	0.06	No/Suggestive

† P-value reflects a two-sided Welch's two sample *t*-test

7.3.4 Presence of Oncoming Vehicle

To address ($H_{0\,(VSP4)}$), which was related to the presence of oncoming vehicular traffic, the dataset was divided by the two levels of oncoming vehicles (no vehicles and three vehicles). These two groups consisted of 10 experimental scenarios each. Figure 7.8 shows the ATFDs with 95% CIs on AOIs by the presence of oncoming vehicular traffic.

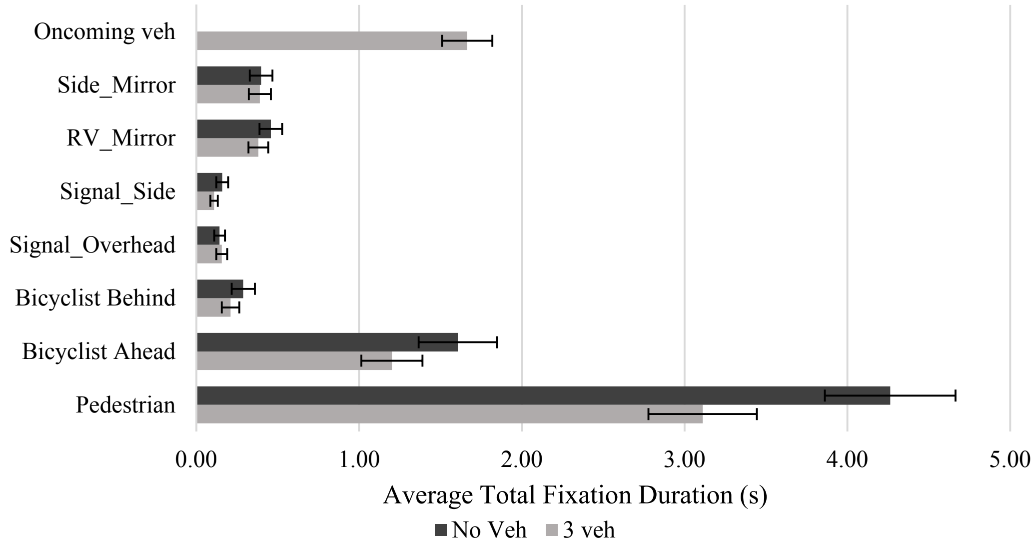


Figure 7.8: Bar plot of ATFDs at all intersections, according to the presence of oncoming vehicle.

Two-sample, two-sided Students or Welch's (when variances were not equal) *t*-tests were conducted to determine whether the ATFDs on specific AOIs varied with the presence of oncoming vehicle (Table 7.5). Statistically significant differences were identified in cases of a pedestrian, a bicyclist riding ahead of the motorist, and side traffic signal AOIs with the presence of oncoming vehicles. Statistical difference indicated that motorists spent less time fixating on the pedestrian, on a bicyclist that was riding ahead of the motorist, and the side signal when there were oncoming vehicles as compared to when there was no oncoming vehicle present. This can be explained by motorists' limited capacity for visual attention. The presence of oncoming vehicles posed more of a threat to the motorist as compared to other objects in his field of view, and as such the motorist spent more time fixating on the oncoming vehicles.

Table 7.5: Two-sample t-test of ATFDs comparing AOIs by oncoming vehicles.

Areas of Interest	Oncoming Vehicle		Two sample two tail *t*-test	
	3 Veh	No Veh	*3 Veh vs No Veh*	
	ATFD (sec)		p-value	Significant
Pedestrian	3.11	4.26	<0.001 †	Yes
Bicyclist Ahead	1.20	1.61	0.01 †	Yes
Bicyclist Behind	0.21	0.29	0.09 †	No
Signal_Overhead	0.16	0.14	0.57	No
Signal_Side	0.11	0.16	0.02 †	Yes
RV_Mirror	0.38	0.46	0.11 †	No
Side_Mirror	0.39	0.40	0.87	No
Oncoming veh	1.67	N/A	N/A	N/A

† P-value reflects a two-sided Welch's two sample *t*-test

7.3.5 Presence of Pedestrian

The influence of a pedestrian was considered to address $H_{0\ (VSP5)}$. For this analysis, the dataset was split by the two levels of conflicting pedestrian in the crosswalk, no pedestrian, or one pedestrian walking towards the motorist. These two groups consisted of 10 experimental scenarios each. Figure 7.9 shows the ATFDs with 95% CIs on AOIs by the presence of a conflicting pedestrian.

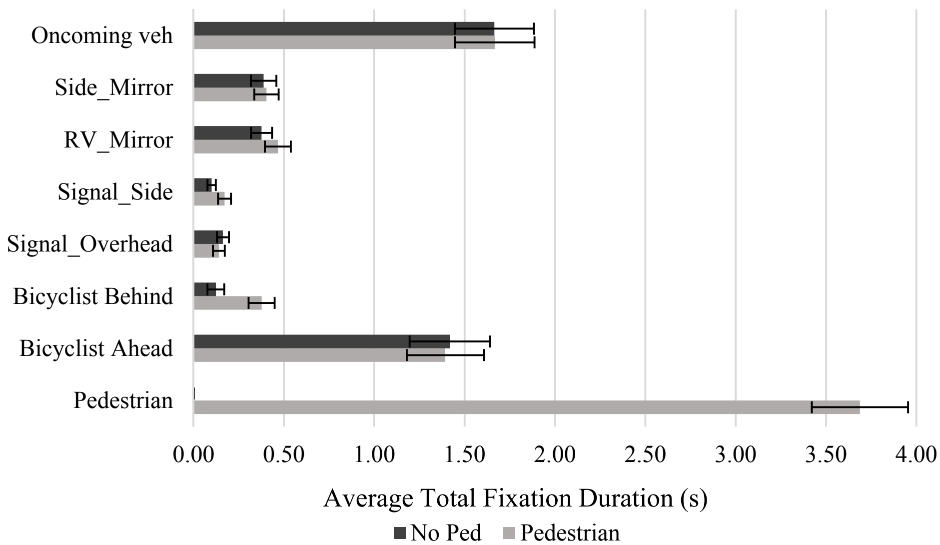


Figure 7.9: Bar plot of ATFDs at all intersections by the presence of pedestrians.

From the result of two-sample, two-sided Students or Welch's *t*-tests (when variances were not equal) (Table 7.6), the only statistically significant difference was found between the ATFD of the bicyclist-behind AOI with the presence of a pedestrian. Results indicated that motorists spent less time fixating on the bicyclist approaching from behind when a conflicting pedestrian was present in the crosswalk as compared to when no pedestrian was present.

Table 7.6: Two-sample t-test of ATFDs comparing AOIs by conflicting pedestrian.

Areas of Interest	Pedestrian		Two sample two tail *t*-test	
	Ped	No Ped	*Ped vs No Ped*	
	ATFD (sec)		p-value	Significant
Pedestrian	3.69	N/A	N/A	N/A
Bicyclist Ahead	1.39	1.42	0.88	No
Bicyclist Behind	0.38	0.12	<0.001 †	Yes
Signal_Overhead	0.14	0.16	0.35	No
Signal_Side	0.17	0.10	0.72	No
RV_Mirror	0.47	0.38	0.06 †	Suggestive
Side_Mirror	0.40	0.39	0.76	No
Oncoming veh	1.67	1.66	0.99	No

† P-value reflects a two-sided Welch's two sample *t*-test

7.4 SUMMARY

This study investigated motorists' visual attention to assess if motorists actively search for bicyclists before turning right at a signalized intersection - an important condition to avoid a right-hook crash. This chapter also examined the effect of various elements of adjacent traffic, such as pedestrians and oncoming vehicles, on motorists' visual attention that may contribute to right-hook crashes.

When a bicyclist was approaching from behind the motorist, they were less likely to be observed by the motorist compared to when bicyclists were riding ahead of the motorist (p-value < 0.001). This finding is consistent with the finding of Falzetta *(Falzetta 2004).* In a simulator-based study, she assessed how the location and the type of events influence motorist attention allocation using an event detection task. The events occurred either ahead of the motorist in the same or the oncoming lane, or behind the motorist. She found that participants detected forward events more successfully than rear events, and the location effect was consistent with an attention allocation strategy that gave higher priority to the road ahead.

For a similar reason, a statistically significant difference (p-value < 0.001) was observed between the frequencies of motorist fixations on the bicyclist when the bicyclist was approaching from behind vs when the bicyclist was riding ahead. Eighty-seven percent of the time motorists fixated on a bicyclist that was riding ahead, whereas the motorist fixated on a bicyclist approaching from behind only 44% of the time.

A statistically significant difference was also observed in the ATFDs on the conflicting pedestrian (p-value = 0.039) and oncoming vehicles (p-value = 0.002) with respect to the bicyclist's position. This finding suggests that when a bicyclist was riding ahead in the motorist's focal vision, motorists anticipated them as a potential collision potential. Therefore, motorists spent less time fixating on other traffic elements, such as a pedestrian or oncoming left-turning traffic in the presence of a bicyclist in the focal vision. However, when the bicyclist was approaching from behind, motorists spent more time fixating on other traffic elements (conflicting pedestrians and oncoming vehicles) immediately relevant to the safe operation of the vehicle.

Another statistically significant finding (p-value = 0.049) was observed in the ATFDs on the right-side mirror when the bicyclist was approaching from behind compared to when there was no bicyclist. This suggests that when motorists detected a bicyclist approaching from behind in the right-side mirror, they spent more time fixating on the right-side mirror while waiting for the bicyclist to pass at the intersection compared to when there was no bicyclist present.

Bicyclists' speed had a statistically significant effect only on the ATFDs on the RV mirror (p-value = 0.03). A bicyclist that was detected in the RV mirror would require more time to travel the same distance before reaching the intersection at lower speed compared to higher speed. Therefore, the total fixation duration spent on checking the RV mirror in search of bicyclist was higher when the bicyclist traveled at a lower speed.

Statistically significant differences in the ATFDs were found on crossing pedestrians (p-value < 0.001), side traffic signal (p-value = 0.022) and bicyclist riding ahead of the motorist (p-value =

0.01) between all intersections with the presence of oncoming left-turning traffic vs no oncoming traffic. Results suggest that in the absence of oncoming traffic, motorists spent more time fixating on other traffic elements in their focal vision, such as scanning for the pedestrian, checking for the traffic signal status, or fixating on the bicyclist ahead. However, in the presence of oncoming vehicular traffic, motorists spent the majority of their time fixating on the oncoming traffic and comparatively less time on the other traffic elements. These findings are similar to the findings of Hurwitz et al., Knodler and Noyce, and Summala et al. *(Hurwitz et al. 2013; Knodler and Noyce 2005; Summala et al. 1996)*. Hurwitz et al studied the effects of the oncoming traffic, the presence and walking direction of pedestrians, and three of four section vertical displays for the Flashing Yellow Arrow (FYA) on driver performance, and found that the oncoming volume of vehicles released from the queue affects the focus of pedestrians on pedestrians *(Hurwitz et al. 2013)*. Knodler and Noyce found that in the absence of opposing vehicles, left-turning drivers were more likely to seek out additional cues *(Knodler and Noyce 2005).* While analyzing bicycle-car collisions at non-signalized intersections in the Helsinki City area, Finland, and by assessing the visual scanning behavior of motorists, Summala et al. found that motorists develop a visual scanning strategy which concentrates on detection of more frequent and major dangers, such as conflicting vehicles, but ignores and may even mask visual information on less frequent dangers, such as bicyclists *(Summala et al. 1996).*

The presence of a pedestrian had a statistically significant effect on the ATFDs of the bicyclist-behind AOI (p-value <0.001). Results suggest that when a conflicting pedestrian was crossing the intersection in the motorist's focal vision, that posed immediate threat to motorists and they spent more time fixating on the pedestrian. Consequently, they failed to fixate on the bicyclist that was approaching from behind in the blind zone.

All these findings indicate that a bicyclist approaching from behind the motorist in the blind spot is the most vulnerable to a right-turning motorist failing to detect this bicyclist and may potentially lead to a right-hook crash. Additional potential conflicts, such as oncoming left-turning traffic and a pedestrian at the crosswalk, also reduce the driver's attention to the bicyclist and are likely to increase the risk of a right-hook crash.

8.0 RESULTS: EXPERIMENT 1 SITUATIONAL AWARENESS

Situational Awareness has been shown to influence both decision making and task performance of the operator during the tasks of driving and flying. While the issue with SA is most pronounced in the aviation domain, other complex real-time tasks such as driving also suffer the consequence of poor SA. An investigation of 2,258 motor vehicle crashes by Treat et al. revealed that improper lookout and inattention, which are two important aspects of SA, were found to be leading causes *(Treat et al. 1980).* Improper lookout or inadequate surveillance consisted both of "failed to look" and "looked but failed to see" *(Treat 1980).* Gugerty found that improper lookout and inattention were cited as causes of more crashes than factors related to decision making (e.g., excessive speed) and psychomotor ability (e.g., improper driving technique) *(Gugerty 2011).* Therefore, measuring the SA of motorists during a right-turning maneuver at an intersection can be useful in the sense that it can provide important insight towards the identification of causal factors of right-hook crashes involving human error. Therefore, this chapter will investigate the SA of motorists completing a right-turn maneuver at a signalized intersection during the latter portion of the green phase.

8.1 DESCRIPTION OF EXPERIMENT

This section describes the procedures and tasks followed in the driving simulator experiment to assess motorists' SA while performing a right-turn maneuver during the latter potion of the green phase at a signalized intersection.

The experiment consisted of a three (bicyclist's relative position) by two (presence of oncoming left-turning vehicle) within-subject factorial design. The task in this experiment used the same experimental design described in Chapter 5. Participants (n=51) were exposed to different combinations of relative positions of a bicyclist and the presence of oncoming left-turning traffic at the last intersection of the first six grids (Table 8.1). Participants were asked to follow the speed limit, which was posted as 35 mph. The average speed of the bicyclist for this experiment was 16 mph at all intersections.

Table 8.1: Layout of the last intersection of each grid.

Grid #	Relative position of bicyclists	Oncoming Traffic
1	1 bicyclist behind	No vehicles
2	1 bicyclist ahead	3 vehicles
3	1 bicyclist behind	3 vehicles
4	No bicyclists	No vehicles
5	No bicyclists	3 vehicles
6	1 bicyclist ahead	No vehicles

8.1.1 **Procedure**

Motorist SA was assessed after completing the right-turning maneuver at the last intersection of each of six grids, as described in Chapter 4. Endsley identified three general components or levels of SA, including perception of elements in the environment (Level 1 SA), comprehension of their meaning in relation to task goals (Level 2 SA), and projection of their status in the near future (Level 3 SA) (*Endsley 1995a &b*). Each of these SA levels was measured using an adaptation of the SA global assessment technique, SAGAT (*Endsley 1988 1995 a &b*). The SAGAT is a simulation freeze technique in which SA queries are presented at random intervals to complex system operators (i.e., pilot, motorist) on the system status, and relevant features of the external environment (*Endsley 1995b*). In this experiment, the simulation was frozen as soon as the motorist completed the last right-turn maneuver in each grid at various points in time. As stated in the "Driving Simulator Study" section in Chapter 4, the grids consisted of varying numbers (two, three or four) of total right-turns and the simulation was frozen at the end of each grid. The total number of right-turns for different grids was not equal so that the simulation could be frozen at various intervals and participants could not predict in advance when the simulation would freeze. During a freeze, the simulation was stopped and the display was blanked out while assessing motorist SA. As soon as the simulation froze, participants were presented with a questionnaire for assessing their SA using a small laptop, and administered through an online survey tool. This procedure was followed to minimize intrusiveness since participants did not need to move to a different workstation to respond to the SA questionnaire. In addition, the computerized versions of SAGAT queries helped to reduce data collection and reduction time when compared to the paper version of queries. There was no time constraint placed on participants to complete the SA questionnaire. After participants completed the questionnaire, the simulation was activated with a new grid of driving scenarios. Participants were not provided with feedback on their responses to the queries during or immediately after the survey.

SAGAT was chosen for this study because it employs objectivity and directedness, and is a well-documented measure of SA (*Gonzalez and Wimisberg 2007*). This deterministic SA measurement has been validated for assessing how aware individuals are about elements in the environment (*Salmon et al. 2009*), which was one of the important objectives of this experiment. SAGAT does not require user self-assessment or any inferences of user behavior. It is also seemingly unobtrusive on the participant's performance because of the short (usually less than one minute) and random interruptions it employs (*Bolstad and Endsley 1990*). Further, no significant effect on participants' performance were found with the number of stops (as many as three for up to two minutes) or duration of stops of up to five minutes (*Endsley 1995 a &b*) in the simulation.

In addition to the explicit recall measures of SA, it is also important to assess operators' SA with indirect performance-based measures since many real-time tasks require well-practiced automatic processes (*Gugerty 1997*). The percentage of times a motorist can avoid hitting an adjacent car positioned in the blind spot during driving is an example of a performance-based measure during the driving task. In this experiment, participants' task performance was measured by investigating if they could avoid a crash with a through-moving adjacent bicyclist to their right while turning right at a signalized intersection during the latter portion of the green phase. As stated in Chapter 4, this performance measure was termed as motorist crash avoidance behavior.

8.1.2 **Presentation of Situational Awareness Questions**

Participants were asked a total of nine SA queries selected from a pool of queries, targeting three questions for each level of motorist SA (perception, comprehension and projection). Each participant received the same nine queries every time, but in a randomized order. The queries were presented randomly so that the participant could not associate any particular question with a particular portion of the driving task while turning at each intersection. The complete SA questionnaire used in this experiment has been included in Appendix E.

Level 1 SA - Perception of the elements in the environment

The first step in achieving SA is to perceive the status, attributes and dynamics of relevant elements in the environment (*Endsley 2001*). To assess Level 1 SA, participants were asked queries to recall the relevant elements in their driving environments, such as the last road sign they saw, the number of bicyclists present in the adjacent bicycle lane, and the number of oncoming vehicles that turned left just before the simulation freeze.

Level 2 SA - Comprehension of the current situation

This level of SA requires the comprehension of the significance of objects and events through the synthesis and integration of disjointed Level 1 elements in conjunction with operator goals (*Endsley, 2001*). Assessment of Level 2 SA included queries that addressed motorists' comprehension of the overall driving environment by investigating whether they could integrate various elements in the built environment, such as the turning signal indicator of the oncoming left-turning vehicles that were waiting in the queue or the current location of a motorist's vehicle with respect to the location where they started driving.

Level 3 SA - Projection of future status

The third and highest level of SA requires the ability to project the future actions of elements in the environment, achieved through the knowledge and comprehension of Level 1 and Level 2 SA. To assess Level 3 SA, participants were asked queries if they could project times to certain events, such as the time required to reach the approaching intersection, or project the location of their vehicle relative to the crossing pedestrian in order to avoid a collision.

Participant's SA was measured by assessing the average percent of correct responses to Level 1, Level 2 and Level 3 queries and an overall SA score (sum of all three SA level scores) across all questionnaires. Participants were not aware of the scoring system.

8.1.3 **Research Objective**

The overarching research objective of this experiment was to assess if right-turning motorists have the necessary knowledge for safely executing a right-turning maneuver, which is important to avoid a potential right-hook crash with an adjacent bicyclist.

8.1.4 **Research Hypotheses**

We hypothesized that right-turning motorists' SA will be affected by the relative position of a bicyclist. We inferred that when a bicyclist approaches from behind a motorist in the adjacent bike lane, the motorist would have comparatively poor knowledge of the bicyclist's presence compared to the scenario where a bicyclist is riding ahead of the motorist in the adjacent bike lane. In particular, Level 1 and Level 2 SA would be poor when bicyclists approach the intersection from behind the motorist as compared to when bicyclists approach the intersection ahead of the motorist due to motorists' poor detection and perception of the traffic element in the driving environment. We also hypothesized that motorists' SA will be reduced when oncoming cars turn left in front of the motorist as they will compete for limited mental resources and will increase motorists' perceptual workload, which will eventually decrease SA (*Gugerty and Garland 2000*). Finally, we hypothesized that the interaction effect of the presence of oncoming vehicles and relative positions of bicyclists will reduce right-turning motorists' SA due to greater demand on working memory load.

We also inferred that a right-turning motorist who will not be able avoid a crash with a through-moving bicyclist has poor knowledge of the bicyclist's location in the adjacent bike lane. Since the SA questionnaire in this experiment involves queries on bicyclist position, we hypothesized that there would be a correlation between motorists' crash avoidance behavior and their SA score, in particular the Level 1 SA score that explicitly assesses the detection of a bicyclist's location.

- $H_{0\ (SA1)}$: Relative positions of adjacent bicyclists' have no effect on right-turning motorists' SA in a driving simulator environment.
- $H_{0\ (SA2)}$: Presence of oncoming left-turning traffic has no effect on right-turning motorists' SA in a driving simulator environment.
- $H_{0\ (SA3)}$: The interaction of left-turning oncoming traffic and relative position of bicyclists have no effect on right-turning motorists' SA in a driving simulator environment.

$H_{0\ (SA4)}$: There is no correlation between the number of correct responses and crash avoidance behavior of right-turning motorists in a driving simulator environment.

8.2 DESCRIPTIVE DATA ANALYSIS

The independent variable was the relative position of bicyclists while approaching the intersection and the presence of oncoming vehicular traffic. Although additional factors, such as the presence of a pedestrian in the conflicting crosswalk, volume of adjacent vehicular traffic, and motorists' experience level, may influence SA, those factors are outside the scope of the current study.

As stated in the "4.2 Research Design" section, the first independent variable was the "relative position of bicyclist," which was manipulated within subjects. It had three levels: 1) no bicyclists, 2) bicyclist approaching from behind the motorist (bicyclist in the blind spot) and 3) bicyclist riding ahead of the motorist (overtaking scenario).) The other independent variable was the "presence of oncoming vehicular traffic," which was also manipulated as a within-subject variable. It had two levels: 1) no oncoming (zero) vehicles and 2) three oncoming vehicles. The levels of each independent variable are listed in Table 8.2.

Table 8.2: Levels of independent variables.

<table>
<tr><th>Name of the Variable</th><th>Category</th><th>Levels</th></tr>
<tr><td rowspan="3">Relative position of bicyclists</td><td rowspan="3">Nominal (Categorical)</td><td>None</td></tr>
<tr><td>One (1) bicyclist riding in front of the motorist in an adjacent bike lane to the right</td></tr>
<tr><td>One (1) bicyclist coming from behind the motorist in an adjacent bike lane to the right</td></tr>
<tr><td rowspan="2">Volume of oncoming vehicular traffic</td><td rowspan="2">Dichotomous (Categorical)</td><td>None</td></tr>
<tr><td>Three (3) Vehicles</td></tr>
</table>

The dependent variables for the experiment were motorists' SA measured through their responses to SAGAT queries in perception (Level 1 SA), comprehension (Level 2 SA) and projection (Level 3 SA) queries and overall SA score across all questionnaires. SAGAT scoring of SA responses are based on binomial data (e.g., correct or incorrect responses) when compared to what was actually happening in the simulation at the time of the freeze.

Participant responses to the SA queries were scored either as 1 (correct) or 0 (incorrect). Participants' overall SAGAT scores for a specific query were calculated by summing all correct responses in Level 1, Level 2, and Level 3 SA queries. Data reduction and visualization was performed in both Microsoft Excel (Microsoft 2013) and SPSS (IBM SPSS Statistics, V22.0), and the statistical analysis was performed in SPSS.

Figure 8.1 presents the mean SA scores to the Level 1, Level 2, Level 3 queries and the mean of overall SA scores as a function of relative position of bicyclists and volume of oncoming vehicular traffic. The plot reveals that, on average, right-turning motorists exhibited better overall SA in the base condition (i.e., when there was no bicyclist or oncoming vehicle present) ($M = 4.88$, $SD = 1.56$) at the intersection and exhibited the worst overall SA when the bicyclist was approaching from behind the motorist, but no oncoming vehicles were present ($M = 3.63$, $SD = 1.76$).

The mean scores in both Level 1 SA ($M = 1.41$, $SD = 0.75$) and Level 2 ($M = 0.90$, $SD = 0.76$) SA were the lowest when an oncoming vehicle was turning in front of the motorist and a bicyclist was approaching from behind. The plot also reveals that right-turning motorists' Level 1 and Level 2 SA scores degraded for the base condition (i.e., when no bicyclist and oncoming vehicles were present).

Unlike the Level 1 and Level 2 SA, the right-turning motorists' Level 3 SA score was the lowest when a bicyclist was riding ahead of the motorist while no oncoming traffic was present ($M = 1.14$, $SD = 0.92$).

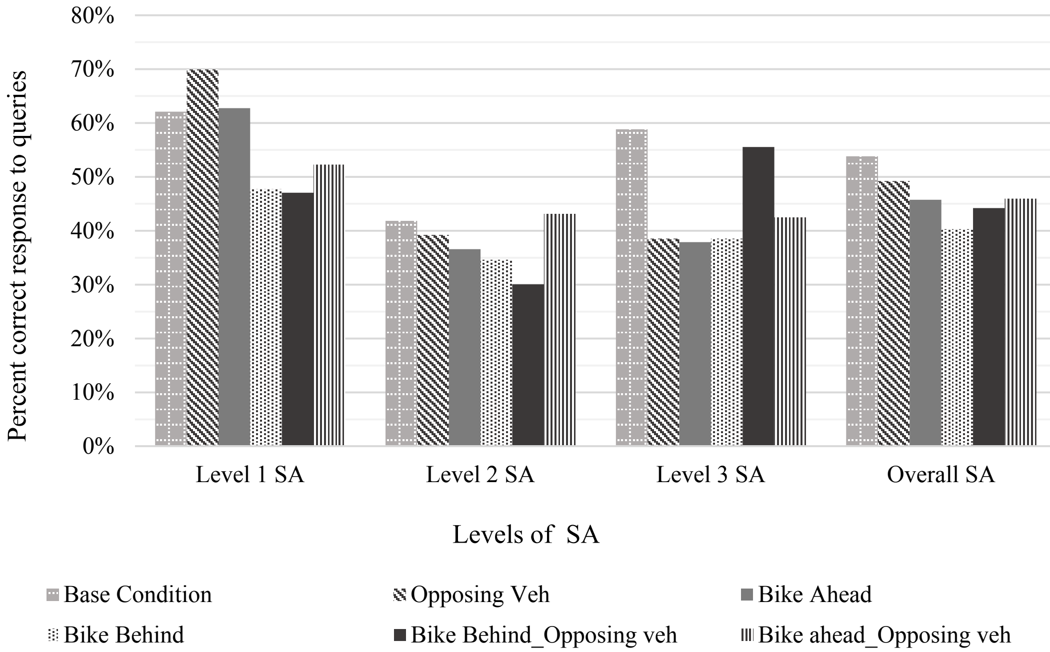


Figure 8.1: Mean percent correct responses to SA queries for bicyclists' position and oncoming vehicular volume.

8.3 STATISTICAL ANALYSIS

A repeated-measure general linear model (GLM) was used for this data analysis. Since the measurements were taken on each participant under each of several conditions, there was a violation of the "independence of observation" condition (*Weinfurt 2000*). Therefore, a "repeated-measures" approach was considered for this data analysis. To control for the experiment-wide error rate associated with conducting multiple analyses of variance (ANOVA) on different dependent variables, a multivariate analysis of variance (MANOVA) was performed (*Kass et al. 2007*). MANOVA accounts for the correlation between the dependent variables (*Mayers 2013*). In addition, a repeated-measures ANOVA is sensitive to the violation of the compound symmetry assumption and the assumption of sphericity (*Weinfurt 2000*). The compound symmetry assumption requires that the variances of the measures (pooled within-group) and covariance between the measures (between-group) at each level of the repeated factor are equal. The sphericity assumption states that the variances of the differences within all combinations of related groups (levels) are equal. When these two assumptions are violated, MANOVA is a more valid and statistically powerful procedure over repeated-measures ANOVA (*Weinfurt 2000*). Considering this, a repeated-measures MANOVA approach was selected to statistically analyze this experimental data set.

In order to perform a MANOVA, the assumptions required were verified for the data set. The independent variables in this data set were categorical, and the dependent variables (SA scores) were interval data. The dependent variables were reasonably normally distributed (skewness and kurtosis z-values between -1.96 to 1.96) and were reasonably correlated (for negative correlation, r < -0.40 and for positive correlation, r < 0.90). Therefore, it was concluded that the data set met the assumption criteria to perform a repeated-measures MANOVA.

The full model in the repeated-measures MANOVA included all of the variables as additive variables. Table 8.3 shows the output of the MANOVA analysis that includes different outcomes for measuring the multivariate significance. According to Bray and Maxwell, Pillai's Trace (V) is the most powerful option when the samples are of equal size (*Bray and Maxwell 1985*). Therefore, results from the Pillai's Trace (V) were considered to report the significance of the test in this experiment.

Repeated-measures MANOVA results (Table 8.3) revealed a significant main effect of the "bicyclist's position" on SA measures ($V = 0.227$, $F\ (2, 49) = 7.183$, p-value = 0.002). Therefore, we rejected the first null hypothesis ($H_{0\ (SA1)}$), which stated that the relative positions of adjacent bicyclists have no effect on right-turning motorists' SA. There was no significant main effect of the "presence of oncoming vehicles." Also, there was no interaction effect of the "bicyclist's position" and "presence of oncoming vehicles." Therefore, we failed to reject the second ($H_{0\ (SA2)}$) and third null hypothesis ($H_{0\ (SA3)}$) of this experiment, which stated the effect of the presence of the oncoming vehicle and the interaction effect on right-turning motorists' SA, respectively.

Table 8.3: Multivariate Statistics

Multivariate Tests[a]							
Effect		**Value**	**F**	**Hypothesis df**	**Error df**	**Sig.**	**Partial eta squared**
BikePos	*Pillai's Trace*	*.227*	*7.183[b]*	*2.000*	*49.000*	*.002*	*.227*
	Wilks' Lambda	.773	7.183[b]	2.000	49.000	.002	.227
	Hotelling's Trace	.293	7.183[b]	2.000	49.000	.002	.227
	Roy's Largest Root	.293	7.183[b]	2.000	49.000	.002	.227
VehVol	Pillai's Trace	.001	.073[b]	1.000	50.000	.789	.001
	Wilks' Lambda	.999	.073[b]	1.000	50.000	.789	.001
	Hotelling's Trace	.001	.073[b]	1.000	50.000	.789	.001
	Roy's Largest Root	.001	.073[b]	1.000	50.000	.789	.001
BikePos * VehVol	Pillai's Trace	.076	2.024[b]	2.000	49.000	.143	.076
	Wilks' Lambda	.924	2.024[b]	2.000	49.000	.143	.076
	Hotelling's Trace	.083	2.024[b]	2.000	49.000	.143	.076
	Roy's Largest Root	.083	2.024[b]	2.000	49.000	.143	.076
a. Design: Intercept Within Subjects Design: BikePos + VehVol + BikePos * VehVol							

Since the MANOVA main effects of bicyclist's position were found, a univariate analysis was examined for this variable. The analysis revealed that right-turning motorists' overall SA score was significantly degraded when a bicyclist was approaching from behind the motorist when compared to no bicyclist presence at the intersection (p-value = 0.001).

A repeated-measures ANOVA was conducted to analyze the Level 1 SA score. Results indicated that there was a significant interaction effect of the bicyclist's position and oncoming vehicular volume on the Level 1 SA score (F (2, 49) = 4.52, p-value=0.013). Motorists' perceptual knowledge of the driving environment was the lowest when a bicyclist approached from behind the motorist and oncoming vehicles were present.

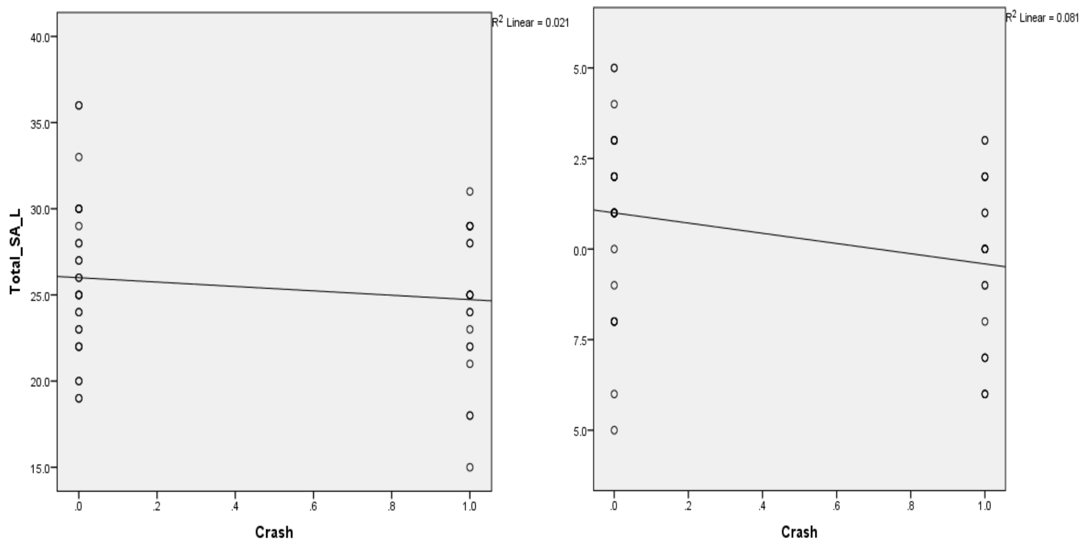
Repeated-measures ANOVA analysis on Level 2 SA scores revealed a significant effect of the bicyclist's position (F (2, 49) = 3.85, p-value = 0.016). No significant effect of the oncoming vehicular volume or interaction effect was found on the Level 2 SA score. A Bonferroni post-hoc analysis indicated that motorists' comprehension of the traffic elements degraded when a bicyclist was approaching from behind the motorist when compared with no bicyclist present (p-value = 0.045) or when the bicyclist was riding ahead of the motorist on the approach to the intersection (p-value = 0.048).

Similar to the Level 1 SA score, a repeated-measures ANOVA analysis on the Level 3 SA score revealed that there was a significant interaction effect of the bicyclist's position and oncoming vehicular volume on a right-turning motorist's Level 3 SA score (F (2, 49) = 8.26, p-value < 0.001). However, unlike the Level 1 SA, motorists demonstrated significantly lower ability to project status of the driving environment when the bicyclist was riding in the front while oncoming vehicles were turning in front of the motorist as compared to when a bicyclist was approaching from behind and oncoming vehicles turned in front of the motorist.

8.3.1 Correlation Analysis

Motorists' crash avoidance behavior was also used as an indicator of their SA while performing a right-turn maneuver at the intersection. In order to determine if there was any significant association between the number of correct responses (i.e., right-turning motorists' overall SA score) and crash avoidance behavior, a Point biserial correlation analysis was conducted between participants' overall SA score and crash occurrence. Participants' crash avoidance behavior was measured in terms of crash occurrence, which was a dichotomous nominal variable and scored either as 1 (crash) or 0 (no crash). Since the Point biserial correlation coefficient (r_{pbi}) indicates the degree of relationship between a naturally occurring dichotomous nominal scale and an interval scale (Brown 1988), it was chosen to calculate the association between crash occurrence (dichotomous variable) and motorists' overall SA score (interval scale).

The Point biserial correlation coefficient (r_{pbi}) *indicated a reasonable negative linear association between overall SA scores and crash occurrence, although not statistically significant* (r_{pbi}= -*0.14, ns). The negative association between overall SA score and crash occurrence (*Figure 8.2 *(a)) indicated that* as a whole *motorist having lower* scores in overall correct responses to SA queries tended to show lower performance in avoiding a crash.



(a) (b)

Figure 8.2 Correlation between crash occurrence and (a) overall SA score, (b) Level 1 SA score.

Since perception and detection of the hazard is an important criterion of crash avoidance, the Point biserial correlation analysis was also conducted between participants' Level 1 SA score and crash occurrence. In this case, The Point biserial correlation coefficient (r_{pbi}) *indicated a significant negative linear association (Figure 8.2(b)) between Level 1 SA score and crash occurrence (r_{pbi}= -0.3, p-value=0.043). This finding suggests that a common cause of the observed crashes was a failure to detect the presence of a conflicting bicycle.*

In summary, the analyses indicated that, on average, the relative position of a bicyclist significantly influenced right-turning motorists' overall SA. The volume of oncoming vehicles was found not to have a statistically significant effect on right-turning motorists' overall SA. The interaction effect between a bicyclist's relative position and oncoming vehicular volume was also found not to have a statistically significant influence on right-turning motorists' overall SA. However, the interaction effect was found to be statistically significant for Level 1 and Level 3 SA. The Point biserial correlation coefficient indicated a reasonable negative linear association between *right-turning* motorists' crash avoidance behavior and overall SA, although not statistically significant. However, a significant negative linear relationship was found between *right-turning* motorists' crash avoidance behavior and Level 1 SA.

8.4 SUMMARY

This study investigated motorists' SA in the real-time complex task of simulated driving as a possible cause of right-hook crashes. Specifically, the objective was to determine if right-turning motorists had the knowledge needed for the driving subtask of monitoring and hazard avoidance, (i.e., the knowledge of the traffic around them) in order to successfully complete a safe right-turn maneuver at a signalized intersection during the latter portion of the green phase.

As expected, participants' overall SA scores indicated that before turning right, motorists were significantly less aware of the presence of bicyclists in the adjacent bike lane when the bicyclist was approaching in an adjacent bicycle lane from behind the motorist as compared to when the bicyclist was riding ahead of the motorist in an adjacent bicycle lane(p-value=0.002). This suggests that right-turning motorists used cues of the surrounding traffic to focus their attention during driving. For example an adjacent bicyclist riding ahead of the motorist posed an immediate driving hazard and they focused more attention on the bicyclist. However, when the bicyclist was approaching from behind in the motorist's blind spot, motorists did not focus attention to the bicyclist in their peripheral vision. This may be due to the fact that tracking an object in the blind spot of a car demands greater working memory (*Gugerty 1997*). This finding is also consistent with previous research by Gugerty, Falzetta, and Crundall et al. (*Gugerty 1997; Falzetta 2004; Crundall et al. 1999*). Gugerty measured motorists' SA through hazard detection, blocking car detection, and crash avoidance during a simulated driving task and found that participants focused more of their attention on nearby cars and cars in front of them that were perceived most likely to pose a hazard and focused less attention on cars in the blind spot (*Gugerty 1997*). While assessing motorists' attention allocation by location and type of event, Falzetta found that participants detected forward events better than rear events, and generally allocated more attention to the road ahead (*Falzetta 2004*). Crundall et al. also found that the frequency of detecting peripheral visual onsets decreased as the cognitive demand of the focal hazard-perception task increased (*Crundall et al. 1999*).

Motorists' perception (Level 1) of traffic was found to be the lowest when oncoming vehicles were turning left in front of the motorist and the bicyclist was approaching from behind (p-value=0.013). This observation could be explained by the cue utilization study, which evaluated the extent to which participants' behavior is constrained by environmental cues *(Brunswick 1956; Hursch et al. 1964).* In this experiment, motorists allocated attention to the oncoming vehicle that posed a potential driving hazard to them, not to the bicyclist in their peripheral vision. Focal hazard-perception tasks compete for limited cognitive resources, which eventually decreased the frequency of detecting peripheral visual events (*Crundall et al. 1999*), as evidenced by decreased Level 1 SA.

Motorists' perception (Level 1 SA) and comprehension (Level 2 SA) of the driving environment was better when the bicyclist was riding ahead as compared to when the bicyclist was approaching from behind. However, an opposing trend was found for Level 3 SA (projection queries), where motorists' projection of the driving environment significantly degraded when the bicyclist was riding ahead of the motorist and oncoming vehicles were turning left in front of the motorist (p-value < 0.001). This can be explained by the limitation of motorists' attentional capacity. With excessive demands on attention due to multiple environmental stimuli (e.g., presence of a bicycle and oncoming cars) to attend to in their focal vision, motorists' task performance declined corresponding to reduced SA.

In the simulated driving task, motorist's perception and comprehension of the driving environments (i.e., lower level SA) also degraded in the scenario where there was no oncoming vehicle and no bicyclist present, although it was not statistically significant. This was likely because in the absence of any type of environmental stimuli (i.e. car, bicyclist), the motorist was not allocating much visual attention to the observation of the driving environment and their knowledge of surrounding traffic degraded.

A significant relationship between motorists' crash avoidance behavior and lower level of SA (perception) suggested that a motorist good at detecting adjacent traffic, might exhibit better crash avoidance behavior with a bicyclist situated in the vehicle's blind spot. This finding suggests that observed crashes were primarily due to the detection error. Gugerty similarly found that better explicit recall of car locations was associated with better performance in hazard detection and blocking car detection (*Gugerty 1997*).

Appropriate caution should be maintained when interpreting the results from this experiment. Motorists with relatively high SA may not always complete the right-turn maneuver successfully by avoiding crashes with a bicycle, whilst relatively poor SA does not necessarily guarantee that a motorist will crash when turning at an intersection. Endsley, for example, indicated that many other factors are involved in turning good SA into successful performance, and it is possible to have bad performance with perfect SA and good performance with poor SA (*Endsley and Garland 2000*).

9.0 RESULTS: EXPERIMENT 1 CRASH AVOIDANCE

This chapter explores the performance of a right-turning motorist through the global performance measure of crash avoidance. Motorists were exposed to crash-likely scenarios in the driving simulator (i.e., oncoming left-turning vehicle, bicyclist in the blind spot, and pedestrians in the conflicting crosswalk) in order to analyze how motorists' behavior contributes to the occurrence of right-hook crashes. This chapter begins with a description of the experiment and then is followed by the data analysis.

9.1 DESCRIPTION OF EXPERIMENT

The objective of this experiment was to assess right-turning motorists' behavior in crash-likely scenarios. Specifically, to assess if motorists can detect the potential hazard (i.e., the bicyclist in the adjacent bicycle lane) and avoid a crash with the bicyclist while performing a right-turn during the latter portion of the green phase at a signalized intersection.

Crash avoidance is measured through the number of right-turning motorists who could not avoid crashes with a through-moving bicyclist to their immediate right in the bike lane at a signalized intersection. It is expected that this global performance measure will provide information on right-turning motorists' decision and response-execution processes, as found by Gugerty (*Gugerty 1997*).

In the research design as discussed in Chapter 5, a bicyclist that posed a potential collision to the motorist was riding in an adjacent bike lane either ahead of the motorist or approaching from behind. The bicyclist approaching the intersection from behind the motorist was entirely within the motorist's blind spot. Since the three-dimensional display in the driving simulator did not show vehicles immediately to the right of the motorist, participants had a larger blind spot than in a real driving environment (*Gugerty 1997*). Participants could avoid colliding with a bicyclist approaching from the behind by detecting it in the rear- or side-view mirror.

While assessing motorists' expectations and mental workload in critical intersection scenarios created in a driving simulator, Plavˇsi´c found that the driving simulator can be successfully deployed to design realistic critical scenarios in urban environments and to explore various driver errors (*Plavˇsi´c 2010*). In this experiment, this crash-likely scenario was created by replicating a complex driving scenario with a significant density of information and variety of vulnerable road users. The crash-likely scenario was replicated at the last experimental intersection (the 21st intersection) of the last grid to avoid any potential impact on motorists' driving task during other scenarios due to the occurrence of a crash. The worst possible condition, identified from the pilot study, was replicated in the crash-likely scenario. In this scenario, an oncoming vehicle made a permitted left turn while the motorist approached the intersection followed immediately by two additional oncoming vehicles waiting in the queue in the opposing left-turn lane, a pedestrian walked towards the motorist in the crosswalk and another vulnerable road user, a bicyclist, approached from behind the motorist in an adjacent bike lane at 16 mph. These traffic elements were situated such that the motorist would likely hit the bicyclist approaching from his vehicle's blind spot unless he detected the bicyclist through his mirrors.

Motorists' crash avoidance behavior was observed during every right-turn maneuver (n = 21), as described in Chapter 4. As previously described, among the 21 right-turning scenarios, a single scenario was designed to be crash-likely, and another 20 scenarios replicated typical intersection scenarios in an urban environment, which were termed as "typical" intersections in this experiment. Motorists driving in the simulated environment were observed continuously from the simulator's operator station and records were taken at the moment a crash occurred. Motorists were also verbally asked at the end of the experiment if they caused any crashes during the experiment. The recorded crash data was further validated by checking the locations of the subject vehicle and bicycle centroid, recorded as dynamic variable data in the driving simulator.

9.2 DATA ANALYSIS

The causes of the crash were assessed through the analysis of participants' eye-tracking data at the time of the crash. Additionally, at the end of the experiment, when participants were verbally asked if they were involved in a crash, they were also asked about the reason for the crash. The responses were then compared with the eye-tracking data. Data reduction and visualization was performed in both Microsoft Excel (*Microsoft 2013*) and SPSS (IBM SPSS Statistics, V22.0), and the statistical analysis was performed in R and SPSS statistical software.

9.2.1 Contributing Crash Factors

In this experiment, 51 participants each completed 21 right-turn maneuvers; in total, 1,071 right-turns were made. Twenty six crashes were observed during 1,071 right-turns. Among these 26 crashes, 11 crashes were observed during the crash-likely scenario and the remaining 15 crashes were observed during the other 20 scenarios (Table 9.1). These 26 crashes were made by 23 participants, three of whom crashed twice. Two of these three participants realized they had been involved in a crash. They stated that although they detected the bicycle in the side-view mirror, the reason of the crash was their poor projection.

Table 9.1: Total number of crashes.

Intersection Type	Crash Number (%)
Typical intersection	15 (58%)
Crash-likely scenario	11 (42%)
Total	26

9.2.1.1 Driving Environmental Factor

The driving environmental factors during observed crashes included the presence of oncoming left-turning traffic, presence of pedestrian in the conflicting crosswalk, and the relative position of a bicyclist in motorist's adjacent bike lane. Table 9.2 describes the exact independent variables that were present in the driving scenario where a crash was observed. After the crash-likely intersection, the highest number of crashes occurred in the typical intersection scenario where the oncoming traffic was present in the conflicting left-turn lane and a bicyclist was approaching from behind at 16 mph, but no pedestrian was present in the conflicting crosswalk.

Apart from the crash-likely intersection scenario, it was found that bicyclists approached from behind the motorist in 13 crash scenarios and bicyclists were riding ahead of the motorist in two crash scenarios. A Chi-square test revealed a statistically significant difference between these two bicyclist positions (p-value = 0.005) with respect to the occurrence of a crash. While the bicyclist's speed was 16 mph in the crash-likely scenario, 12 typical intersection crash scenarios had bicyclists approaching at 16 mph speed and three crash scenarios had bicyclists approaching at 12 mph speed. A Chi-square test revealed a statistically significant difference between bicyclist speeds with respect to crash outcomes (p-value = 0.02). The average motorist speed during crashes at the crash-likely scenario was 12.6 mph, ranging from a minimum of 7.2 mph to a maximum speed of 19.7 mph.

Thirteen crash scenarios had a pedestrian in the conflicting crosswalk, whereas 13 crashes occurred when no pedestrian was present. No statistically significant difference was found for the presence of pedestrians with respect to crash outcomes. Motorists caused 21 crashes when oncoming left-turning vehicles were present, whereas seven crashes occurred when no oncoming vehicle was present. A statistically significant difference was found for the presence of oncoming vehicles with respect to crash outcomes (p-value = 0.008).

Table 9.2: Independent variable levels during observed crashes.

Intersection Type	Relative Position of Bicyclist	Oncoming Traffic Volume	Bicyclist Speed (mph)	Motorist Speed (mph)			Crossing Pedestrian	Total
				Mean	Max	Min		
Crash-Likely Intersection (n=11)	1 bicyclist behind	3 veh	16	12.6	19.7	7.2	1 ped	11
Typical Intersection (n=15)	1 bicyclist behind	3 veh	16	10.5	12.3	9.1	None	6
	1 bicyclist behind	None	16	11.9	12.5	11.4	None	3
	1 bicyclist ahead	None	16	11.9	11.9	11.9	None	1
	1 bicyclist behind	3 veh	16	8.9	8.9	8.9	1 ped	1
	1 bicyclist behind	3 veh	12	8.5	8.5	8.5	None	1
	1 bicyclist ahead	None	12	7.6	7.6	7.6	None	1
	1 bicyclist behind	None	12	9.5	9.5	9.5	None	1
	1 bicyclist behind	None	16	12.6	12.6	12.6	1 ped	1
	Total							26

9.2.1.2 Motorist-Related Factors

Motorist-related factors of crashes are categorized into two groups - factors attributed to motorist characteristics, such as gender, age, education and experience, and factors attributed to motorist behavior characteristics, such as inadequate surveillance and poor projection.

Analysis of the participant demographics showed that male participants were more likely to be involved in crashes than female participants (Table 9.3). A Chi-square test revealed statistically significant differences between gender with respect to crash involvement (p-value = 0.02). Although the highest percentage of motorists had driving experience of 1-5 years (44%), no statistically significant difference in crash involvement was found with respect to driving experience. Table 9.3 also indicates the highest number of participants involved in a crash attended some college (31%) and were between the ages of 25-34 years (39%), and no statistically significant effect on crash involvement was found with respect to education or age.

Table 9.3: Motorist-related crash causal factors.

Category	Level	Overall Demographics	Crash-Likely Scenario (n=11)	Other Scenarios (n=12)	Total (n=23)
Gender	Male	59 %	73%	75%	74%
	Female	41 %	27%	25%	26%
Experience (year)	1-5	37%	45%	42%	44%
	6-10	27 %	27%	8%	17%
	11-20	8 %	9%	17%	13%
	20+	4%	18%	33%	26%
Education	High School	4 %	0%	8%	4%
	Some College	33 %	27%	33%	31%
	Associates Degree	12 %	18%	8%	13%
	4 year degree	25 %	18%	33%	26%
	Master's Degree	22 %	18%	17%	17%
	PhD Degree	4 %	18%	0%	9%
Age (year)	18-24		36%	33%	35%
	25-34		45%	33%	39%
	35-44		9%	8%	9%
	45-54		0%	8%	4%
	55-64		9%	8%	9%
	65+		0%	8%	4%
Cause	Fails to look (Improper Lookout)	n/a	64%	67%	66%
	Look but did not see (Improper Lookout)	n/a	27%	7%	15%
	Poor Projection	n/a	9%	26%	19%

9.2.1.3 Factors Related to Motorist Behavior

Causal factors attributed to motorist behavior were categorized as either inadequate surveillance or poor projection. As stated in Chapter 2, inadequate surveillance occurs when a motorist either fails to look or looks but does not see (inattention blindness). Analyzing motorists' glance data from the eye tracker, it was found that in most cases (66%) motorists did not check their mirrors before turning right and failed to detect the bicyclist in their blind spot (Table 9.3). This finding was consistent with responses to follow-up questions collected at the end of each experiment drive. However, 15% of the motorists who were involved in crashes said that they did not see any bicyclist before turning right, although their glance data revealed that they had checked at least one mirror before turning and the bicyclist was visible in that mirror. It indicated that those crashes may have been the result of a "look but did not see" failure.

Five of these 26 crashes (19%) occurred due to poor motorist projection (Table 9.3). In two of those crash scenarios, a bicyclist was riding ahead of the motorist; the motorist passed the bicyclist and then turned right at the intersection. By not yielding the right-of-way to the bicyclist, a crash resulted. In the other three cases, the bicyclist approached from behind the motorist and the motorist detected the bicyclist in one of the mirrors. Motorists' detection of the bicyclist was confirmed from their verbal statement and glance data. However, motorists reported that they assumed they would be able to complete the right-turning maneuver before the bicyclist reached the intersection. Due to motorists' poor projection, a crash with the bicyclist resulted during the turning maneuver.

9.2.2 Analysis of Simulator Crash Events

To aid in the preliminary data exploration, collision diagrams were created for each right-turning scenario that experienced crashes. The collision diagram focuses on right-turning vehicle trajectories and through-moving bicyclist trajectories at the intersection. The collision diagrams zoom in on the corner of the intersection where the right-turn maneuvers took place. Therefore, only the shared through right lane from the east and the shared receiving lane to the north, including the bike lanes, have been shown in the collision diagram. The diagram also identifies the location of the crashes, the crash sequence number, the traffic signal status, which was green during all crashes, and the speed of the motorists and bicyclists in mph at the time of collision.

Figure 9.1 presents a collision diagram of crashes that specifically occurred in the crash-likely scenario. The diagram shows 12-foot-wide vehicle approaching and receiving lanes, 5.5-foot-wide bike lanes, vehicle trajectories, and the bicyclist's speed (16 mph) and direction of travel. As the crash sequence number indicates in the diagram, there were 11 crashes at this intersection, with a variety of vehicle speeds. The diagram also indicates crash locations occurring from the edge (crash#7) to the middle of the intersection (crash#4).

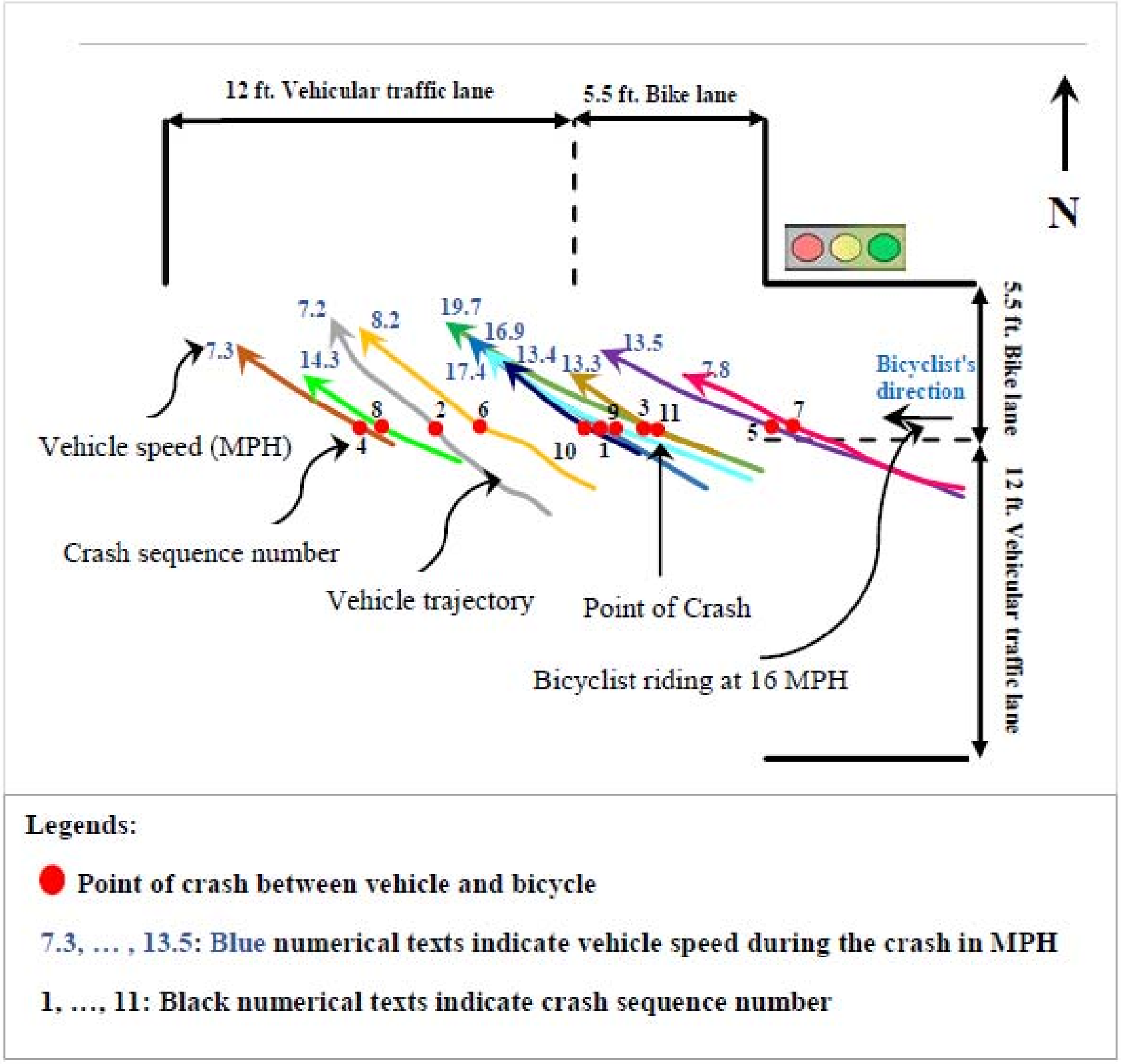


Figure 9.1: Collision diagram of the crashes occurred in the crash-likely intersection.

9.2.3 Analysis of Conflicts

Near-crashes, or traffic conflicts between a right-turning motorist and through-moving bicyclist, where calculated where a collision was imminent if the trajectories remained unchanged. The majority of the right-hook crashes occurred when a bicyclist was approaching from behind and to the right in the motorist's blind spot. Therefore, the traffic conflicts for the typical intersection scenarios, where the bicyclist was approaching from behind the motorist, were investigated to further assess the risk of collisions through TTC. A simple form of the TTC calculation for a right-hook crash scenario was developed in Figure 9.2, where the bicyclist was approaching from behind the motorist.

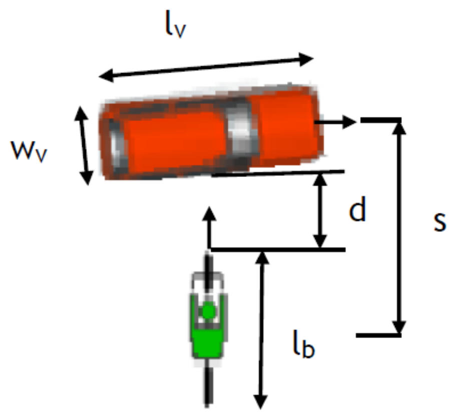


Figure 9.2: TTC calculation for a right-hook crash scenario

Since, the location of the vehicle and bicycle centroids was recorded in the driving simulator, distances between the vehicle and the bicyclist were calculated from their centroids. Therefore,

$$\boldsymbol{TTC = \frac{d}{v_b}} \qquad \textit{Equation 9.1}$$

$$\boldsymbol{d = s - \frac{w_v}{2} - \frac{l_b}{2}} \qquad \textbf{Equation 9.2}$$

where,

w_v = width of vehicle (i.e., car)
l_b and l_v = length of bicycle and car, respectively
v_b and v_v = velocity of bicycle and car, respectively
d = distance from middle point of the side of the car and front of the bicycle
s = center to center distance between bicycle and car

9.2.3.1 Data Analysis and Result

Using Equation 9.1 and Equation 9.2, the TTC was calculated for eight typical intersections where the bicyclist was approaching from behind the motorist. The calculated TTCs were classified according to Table 2.4.

Table 9.4 displays the number of traffic conflicts, and corresponding TTC values, for eight typical intersections where the bicyclist was approaching from behind the motorist and the motorist was exposed to other experimental factors present in that driving scenarios. There were a total 159 conflict events among 408 (51*8) right-turns. However, according to the 1.5second TTC threshold value and the ROC score (*Brown 1994; Gettman et al. 2008; Sayed et al. 1999*), only 26 incidents could be considered having high (0-0.9 seconds) (n=8) or moderate risk (1.0-1.5 seconds) (n=18) TTC values.

Table 9.4: Number of traffic conflicts and Time to Collision (TTC) (s).

Relative position of bicyclist	Oncoming traffic Volume	Bicyclist Speed (mph)	Crossing ped	TTC (sec)				Total
				0-0.9	1.0-1.5	1.6-2.0	2.0+	
1 bicyclist behind	None	16	None	2 (7%)	5 (17%)	9 (31%)	13 (45%)	29
1 bicyclist behind	None	12	None	2(6%)	4 (11%)	4 (11%)	26 (72%)	36
1 bicyclist behind	None	16	1 ped	0 (0%)	0 (0%)	0 (0%)	23 (100%)	23
1 bicyclist behind	3 veh	16	None	3 (14%)	3 (14%)	8 (36%)	8 (36%)	22
1 bicyclist behind	3 veh	16	1 ped	1 (10%)	1 (10%)	2 (20%)	6 (60%)	10
1 bicyclist behind	3 veh	12	None	0 (0%)	4 (14%)	1 (3%)	24 (83%)	29
1 bicyclist behind	None	16	1 ped	0 (0%)	0 (0%)	0 (0%)	4 (100%)	4
1 bicyclist behind	3 veh	12	1 ped	0 (0%)	1 (17%)	0 (0%)	5 (83%)	6
Total				8 (5%)	18 (11%)	24 (15%)	109 (69%)	159

The frequency and cumulative frequency distribution were plotted for the above intersections. Figure 9.3 demonstrates the frequency distribution and cumulative frequency distribution for one of the right-turning intersections (one bicyclist approaching at 16 mph from behind, three oncoming vehicles and no pedestrian). It can be seen that 27% of the traffic conflicts had TTCs equal to or less than 1.5 seconds. Similar plots for traffic conflicts at the other seven intersections have been provided in Appendix F.

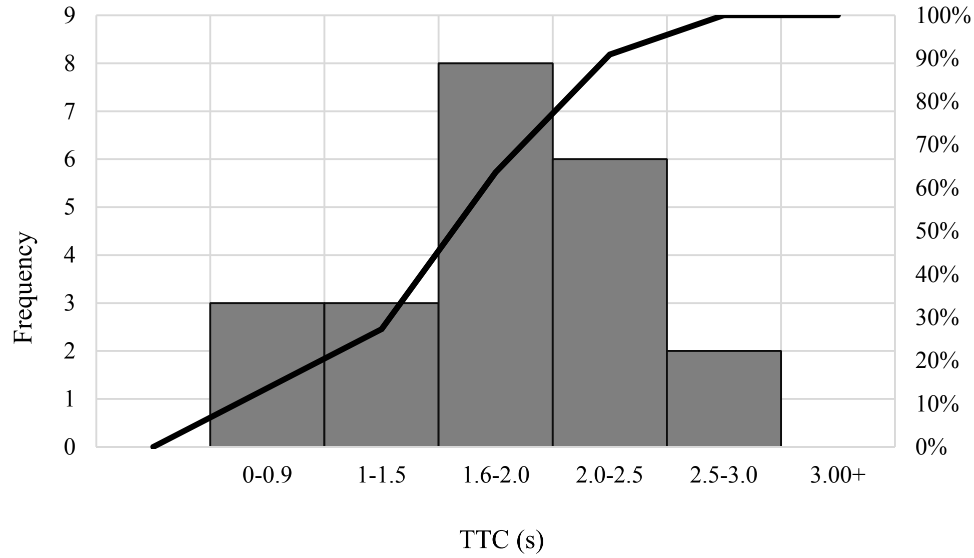


Figure 9.3: Frequency and cumulative frequency distribution curve for the intersections with a bicyclist (16 mph) behind, three oncoming vehicles, and no ped.

Table 9.5 describes the motorist-related causal factors of the 26 severe near-crash scenarios. It was found that the eight high-risk traffic conflicts (TTC ≤ 0.9 sec) were contributed by seven participants (i.e., one participant was involved in two near-crash incidents). For the moderate-risk traffic conflict (TTC = 1.0-1.5 sec), 14 participants were involved in 16 traffic conflicts. Also, one participant had both high-risk (TTC ≤ 0.9 sec) and moderate-risk (TTC = 1.0-1.5 sec) traffic conflicts in two different intersections. In summary, it was found that 20 participants were involved in a total of 26 severe near-crashes.

Table 9.5: Motorist related causal factors for near-crash incidents.

Category	Level	Demographics (n=51)	TTC (sec)		
			0-0.9 (n=7)	1-1.5 (n=14)	Total (n=20)
Gender	Male	59 %	71%	64%	70%
	Female	41 %	29%	36%	30%
Experience (year)	1-5	37%	29%	50%	40%
	6-10	27 %	14%	21%	20%
	11-20	8 %	14%	14%	15%
	20+	4%	43%	14%	25%
Education	High School	4 %	0%	7%	5%
	Some College	33 %	29%	57%	40%
	Associates Degree	12 %	14%	0%	5%
	4 year degree	25 %	43%	7%	20%
	Master's Degree	22 %	14%	21%	20%
	PhD Degree	4 %	0%	7%	5%
Age (year)	18-24	43%	43%	64%	55%
	25-34	33%	14%	21%	20%
	35-44	8%	14%	7%	10%
	45-54	2%	0%	0%	0%
	55-64	6%	14%	7%	10%
	65+	8%	14%	0%	5%
Cause	Fails to look (Improper Lookout)	29%	78%	47%	58%
	Look but did not see (Improper Lookout)	12%	22%	24%	23%
	Poor Projection	10%	0%	29%	19%

As found from Table 9.5, males were more involved in near-crash incidents than females. More participants involved in near-crashes had 1-5 years of driving experience, went to some college, and were between the ages of 18-24 years. Motorists' glance data revealed that, in most cases, in particular for high-risk conflicts, 78% of the time motorists did not check their mirrors before turning right and, as a result, failed to detect a bicyclist in their blind spot. In 23% of the conflicts, participants glanced at a mirror once or twice when the bicyclist was visible, but the motorist failed to yield the right-of-way. This glance type was considered to be a "look but did not see" failure, often referred to as an inadequate surveillance error. In some cases, motorists checked the mirror more than twice and fixated on the bicyclist, but still failed to yield the right-of-way. This type of error was considered as "poor projection," which accounted for 19% of the near-crash causes. Another interesting point of the near-crash analysis revealed that 11 (54%) of the 20 participants involved in a near-crash experienced a crash in one of the intersections in the complete experiment.

9.3 SUMMARY

The performance of a right-turning motorist was assessed through the global performance measure of crash avoidance. The crash avoidance behavior observed in this experiment indicated motorists' ability to detect a bicyclist in a timely manner and make an appropriate decision to avoid a crash with that bicyclist while turning right at a signalized intersection.

Among 51 participants completing a total of 1,071 right-turns, 23 participants could not avoid a crash with a bicyclist in 26 right-hook crash scenarios. Relative position of a bicyclist, the bicyclist's speed, and the presence of an oncoming left-turning vehicle were found to have a significant effect on crashes. This finding is consistent with the finding from Chapter 5 and Chapter 6, that when motorists' dynamic working memory is overloaded due to the presence of adjacent traffic on the roadway, they focus their attention to the immediate hazard in their forward visual field (i.e., the oncoming traffic) and did not shift their attention to the rear- and side-view mirrors to check for the presence of a bicyclist in their blind spot. Also, higher speed of bicyclists was found to be a significant crash contributing factor, as reported by the survey respondents in Chapter 2.

Male participants were involved in more right-hook crashes than female participants, with statistical significance (p-value = 0.02). A binary logistic regression conducted to assess the probability of a right-hook crash occurrence given the demographics of participants in this experiment also revealed that gender was a significant predictor of crash involvement.

Motorists' inadequate surveillance was found to be the major cause of observed right-hook crashes, where the motorist did not check for the bicyclist in the mirror before turning in most cases (66%) or looked but did not see (inattention blindness) in some cases (15%). Some right-hook crashes (19%) were caused due to motorists' poor projection, where he detected the conflicting bicyclist but did not yield the right-of-way.

Collision diagrams were created to visualize the observed right-hook crashes with vehicle and bicycle trajectories, their speed and crash locations.

Investigation of near- crash incidents revealed that among 51 participants completing a total of 408 right-turns, 20 were involved in 26 severe near-crash incidents having TTC value less than or equal to 1.5 seconds. Inadequate surveillance was found to be the cause of most near-crash incidents. Eleven of these 20 participants were also found to ultimately have a crash in the experiment, suggesting their susceptibility to right-hook crash scenarios.

10.0 RESULTS: FIELD VALIDATION

This chapter explores how well the field-observed behaviors of a right-turning motorist map to the behaviors in the driving simulator. As discussed in the methodology chapter, the primary behaviors that were mapped are the Post Encroachment Time (PET) metric and speed of the bicycles. The first section summarizes the data collection effort and is followed by a descriptive summary of all the potential conflicts. Next, the distribution of the PET values is compared between the field and simulator TTC values statistically. Finally, a summary of the analysis is presented. Note that the analysis in this chapter only relates to the Experiment 1 measured values.

10.1 SUMMARY OF DATA COLLECTION

The data collection took place from November 5, 2014 to February 12, 2015. The weather in early November 2014 was unseasonably warm and bicycle traffic was still good. The winter of 2014-15 has been one of the warmest on record, so there was still sufficient bicycle traffic. After preliminary analysis, however, it was clear that measurable conflicts would be on about one conflict for every three hours of video. To obtain a sufficient sample, the video data collection was extended into January and February of 2015.

Table 10.1: Date, hours, weather conditions, and frequency of Post Encroachment Times (PET).

Date	Day	Recording Time	Weather	Temperature, F^o (Low – High)	Number of Events (PETs)	Hours of Video
11/5/2014	Wednesday	10 AM - 5 PM	Clear	$54^o – 62^o$	2	7
11/6/2014	Thursday	7 AM - 5 PM	Rainy	$51^o – 61^o$	5	10
11/7/2014	Friday	7 AM - 5 PM	Clear	$44^o – 57^o$	5	10
11/8/2014	Saturday	7 AM - 3 PM	Clear	$41^o – 58^o$	1	8
11/9/2014	Sunday	9 AM - 5 PM	Clear	$44^o – 56^o$	3	8
11/10/2014	Monday	7 AM - 5 PM	Clear	$42^o – 58^o$	4	10
11/11/2014	Tuesday	7 AM - 5 PM	Clear	$35^o – 47^o$	2	10
11/12/2014	Wednesday	7 AM - 5 PM	Clear	$32^o – 41^o$	3	10
1/21/2015	Wednesday	4 PM - 6 PM	Clear	$31^o – 49^o$	2	2
1/22/2015	Thursday	12 PM - 6 PM	Clear	$40^o – 46^o$	0	6
1/23/2015	Friday	12 PM - 6 PM	Light Rain	$42^o – 46^o$	1	6
1/24/2015	Saturday	12 PM - 6 PM	Clear	$43^o – 60^o$	3	6
2/6/2015	Friday	9 AM - 7 PM	Rainy/Windy	$48^o – 57^o$	0	10
2/7/2015	Saturday	9 AM - 7 PM	Rainy/Windy	$49^o – 59^o$	4	10
2/8/2015	Sunday	9 AM - 5 PM	Rainy/Windy	$46^o – 57^o$	0	8
2/9/2015	Monday	9 AM - 2 PM	Rainy/Windy	$46^o – 53^o$	1	5
2/10/2015	Tuesday	9 AM - 5 PM	Clear	$45^o – 55^o$	2	8
2/11/2015	Wednesday	9 AM - 5 PM	Clear	$40^o – 57^o$	5	10
2/12/2015	Thursday	9 AM – 7 PM	Clear	$37^o – 63^o$	0	10
				Total	**43**	**144**

10.2 DESCRIPTIVE DATA ANALYSIS

Table 10.2 summarizes each of the field observed events where the PET was measured at less than five seconds. The table lists the date, time, vehicle type, the measured PET, the measured speed of the bicyclist, whether there was a pedestrian and the number of bicyclists that were approaching from behind. The average field-measured PET was 3.05 seconds; the smallest value was 1.20 seconds. The maximum value was 4.97 seconds (values longer than this were excluded from the field measured data). The average speed of the observed bicycles was 12.61 mph with a minimum of 8.61 mph and a maximum of 18.18 mph. Pedestrians were present in the crosswalk for only four of the observations. In four situations there were two bicyclists approaching, which was not a scenario in the simulator.

Table 10.2: Summary of field-observed PETs (s) ≤ 5 (s).

Date	Time	Vehicle Type	PET (Sec)	Bicyclist Speed (mph)	Crossing Pedestrian	Relative Position of Bicyclist
11/5/2014	11:57:13	Car	2.20	10.68	None	1 bicyclist behind
11/5/2014	14:47:40	Car	3.20	12.29	None	1 bicyclist behind
11/6/2014	8:29:54	Pick up	1.87	9.10	None	1 bicyclist behind
11/6/2014	11:01:05	Car	1.50	16.38	None	1 bicyclist behind
11/6/2014	12:46:46	Car	4.40	13.65	None	1 bicyclist behind
11/6/2014	15:07:09	Car	4.97	13.65	None	1 bicyclist behind
11/6/2014	16:58:58	Car	2.73	13.65	None	1 bicyclist behind
11/7/2014	8:52:43	SUV	3.50	12.93	None	1 bicyclist behind
11/7/2014	12:12:10	Pick up	3.00	16.38	None	1 bicyclist behind
11/7/2014	13:49:23	Van	4.90	13.65	None	1 bicyclist behind
11/7/2014	15:35:29	SUV	1.30	12.93	None	1 bicyclist behind
11/7/2014	16:18:51	Car	1.83	11.17	None	1 bicyclist behind
11/8/2014	12:05:55	Car	3.83	11.70	None	1 bicyclist behind
11/9/2014	9:19:42	SUV	4.27	16.38	None	1 bicyclist behind
11/9/2014	12:45:46	Car	3.50	15.36	None	1 bicyclist behind
11/9/2014	16:02:45	Car	3.30	10.68	1 ped	1 bicyclist behind
11/10/2014	8:01:21	Van	4.37	11.17	None	1 bicyclist behind
11/10/2014	10:59:52	Pick up	3.77	11.17	None	1 bicyclist behind
11/10/2014	11:38:33	Car	4.00	14.45	None	1 bicyclist behind
11/10/2014	12:10:38	Car	2.07	12.93	None	1 bicyclist behind
11/11/2014	12:48:19	SUV	2.57	12.93	None	1 bicyclist behind
11/11/2014	16:54:40	Car	2.70	13.65	None	1 bicyclist behind
11/12/2014	15:05:53	Car	2.50	9.10	None	1 bicyclist behind
11/12/2014	15:29:38	Car	3.43	12.29	None	1 bicyclist behind
11/12/2014	15:35:35	Car	3.40	13.65	None	1 bicyclist behind
1/21/2015	16:19:50	Car	1.90	9.63	None	1 bicyclist behind
1/21/2015	17:46:06	SUV	2.90	13.64	None	1 bicyclist behind
1/23/2015	12:05:52	BUS	1.50	10.91	1 ped	1 bicyclist behind
1/24/2015	14:44:57	Pick up	3.30	9.63	None	1 bicyclist behind
1/24/2015	15:03:25	SUV	1.80	10.91	None	2 bicyclist behind
1/24/2015	17:53:05	Pick up	2.40	10.23	None	1 bicyclist behind
2/7/2015	12:18:53	Car	1.20	10.91	None	1 bicyclist behind
2/7/2015	12:49:18	Car	3.30	11.69	None	2 bicyclist behind
2/7/2015	13:11:59	Car	2.80	14.88	None	1 bicyclist behind
2/7/2015	15:26:24	SUV	4.50	10.91	1 ped	2 bicyclist behind
2/9/2015	11:00:16	Car	2.15	12.59	None	1 bicyclist behind
2/10/2015	11:37:41	SUV	2.35	10.23	None	1 bicyclist behind
2/10/2015	15:53:07	Car	2.55	12.587	None	1 bicyclist behind
2/11/2015	10:14:02	Pick up	3.85	14.88	None	1 bicyclist behind

Date	Time	Vehicle Type	PET (Sec)	Bicyclist Speed (mph)	Crossing Pedestrian	Relative Position of Bicyclist
2/11/2015	12:34:59	SUV	4.90	8.61	1 ped	1 bicyclist behind
2/11/2015	15:59:17	Car	2.85	14.88	None	1 bicyclist behind
2/11/2015	18:22:59	Car	3.35	14.87	None	2 bicyclist behind
2/11/2015	18:57:52	Car	4.45	18.18	None	1 bicyclist behind
Average			3.05	12.61		
Standard Deviation			1.03	2.24		
Minimum			1.20	8.61		
Maximum			4.97	18.18		

10.3 COMPARISON OF SIMULATOR DATA WITH FIELD OBSERVATIONS

By utilizing video footage collected in the field, driver behaviors between the field and the simulator were compared. The goal of this process was to validate that the simulator closely reflected actual driving conditions. Of the vehicles observed turning right when a bicyclist was approaching from behind (PET/TTCs ≤ 5 sec), there were 43 records from the field and 159 records from the simulator. However, because there was a left-turn lane with separate signal timing in the field, the right-turning vehicles didn't actually conflict with the oncoming left-turning vehicles so PET/TTCs for events with the presence of oncoming left-turning vehicles in the simulator were not considered. Overall, 86 records of TTCs from the simulator were compared to 43 records from the field-observed data.

10.3.1 Comparison of All Observations

PET/TTCs were grouped into six time intervals. They represent the level of near-crash incidents, including high risk (PET/TTC ≤ 0.9 sec), moderate risk (PET/TTC=1.0-1.5 sec), low risk (PET/TTC=1.6-2.0 sec), and possible interaction (PET/TTC ≥ 2+ sec). To have a better distribution of data, possible interaction was divided into three levels (PET/TTC=2.0-2.5 sec), (PET/TTC=2.5-3 sec), and (3 < PET/TTC ≤ 5 sec). The number of PET/TTCs for each group of near-crash incidents is shown in Table 10.3 for both the field observation and driving simulator.

Table 10.3: Number of traffic conflicts by PET/TTC (sec) bins.

	PET/TTC (sec)						Total
	0.0-0.9	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3+	
Field	0	4	4	6	8	21	43
Simulator	4	9	14	15	17	27	86

A Chi-square test for goodness of fit was conducted to evaluate whether the field data show the expected distribution of driver behaviors. In order to execute a correct Chi-square approximation, the sample sizes of two groups (high risk, moderate risk) that had small observations in the field were summed. The result indicated that the simulator and field-observed proportions were not significantly different ($p = 0.365$). The sample size (bars) and cumulative percent (line) of each group of observations are displayed in Figure 10.1. The sample size percentage of each group of observations is displayed within each respective bar in Figure 10.2. From the plots, it is clear that the field-observed PET distribution maps well to the simulator-observed TTCs. As would be expected, the simulator has more observations of smaller TTCs due to the intentional loading in the simulator and the ability of bicycles to decelerate in the field measured PETs.

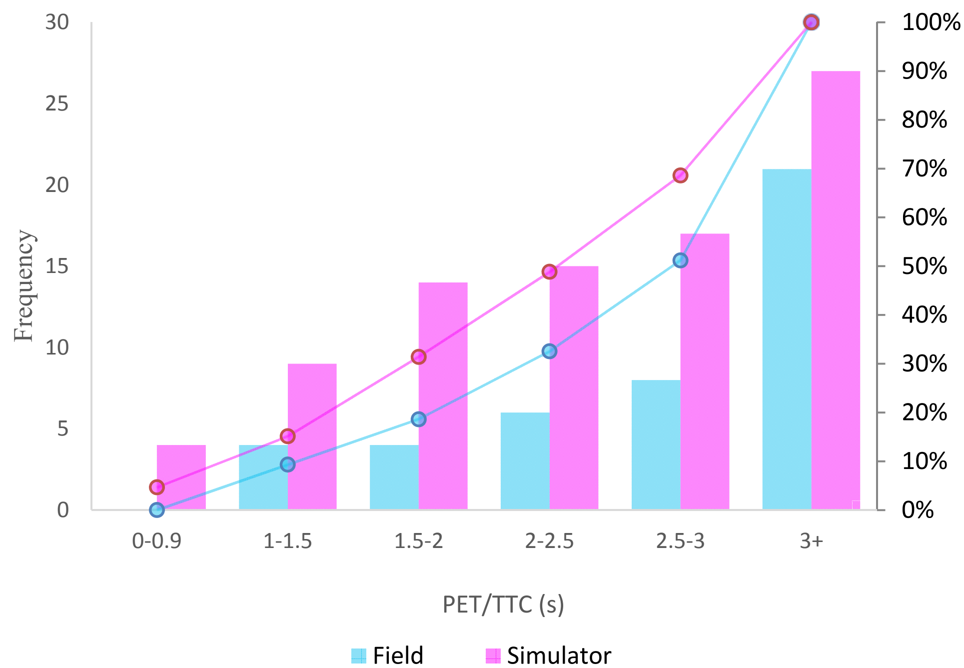


Figure 10.1: Frequency (left axis) and cumulative percent (right axis) of PET/TTC values, all observations.

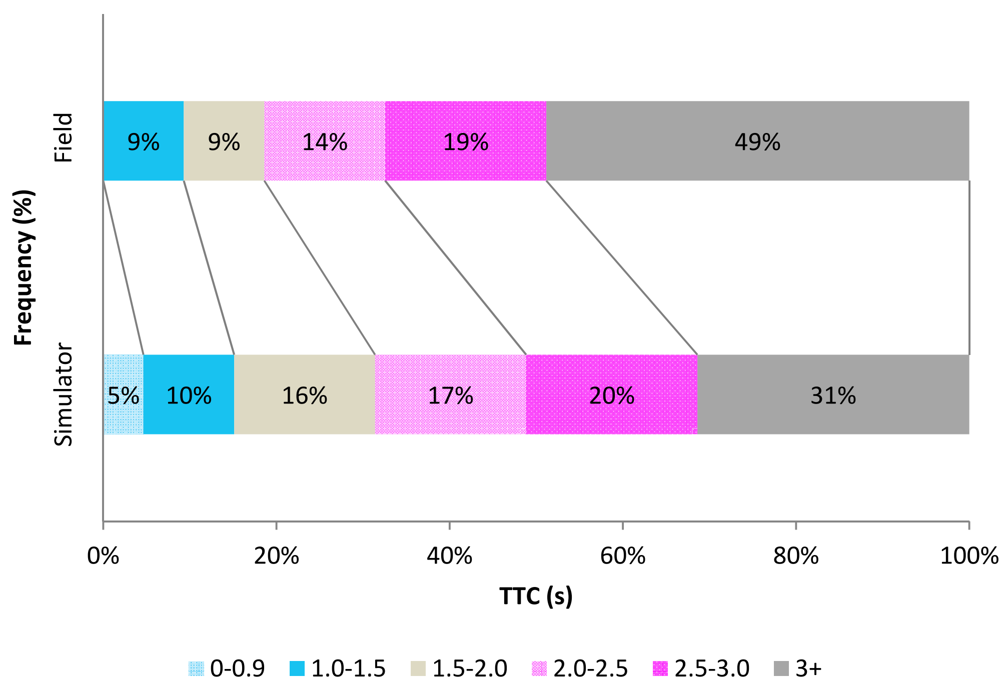


Figure 10.2: Distribution of PET/TTCs, all observations.

10.3.2 Comparison of PET/TTCs Matched to Simulator Scenarios

The various scenarios were designed and analyzed in the simulator setting. TTCs were categorized into eight scenarios. These scenarios included the combination of three factors: (1) “Bicyclist speed” which had two levels: low (12 mph), and high (16 mph); (2) The “presence of oncoming left-turning vehicular traffic,” which had two levels: no oncoming (zero) vehicles, and three oncoming vehicles; (3) The “presence of a conflicting pedestrian in the crosswalk,” which also had two levels: no pedestrian and one conflicting pedestrian walking towards the participant.

As noted, the field observation has no oncoming left-turn vehicles, so that left four possible scenarios to compare. Further, the field-observed speed of bicyclists is not fixed so to make further comparison the speed of observations in the field was divided into two levels: high speed (> 14 mph) and low speed (≤ 14 mph). The scenarios and the number of TTCs are shown in Table 10.4 for the simulator and Table 10.5 for the field observations.

Table 10.4: Scenarios and number of traffic conflicts (TTCs) in the simulator.

Simulator	Relative position of bicyclist	Bicyclist speed (mph)	Crossing ped	TTC (sec)				Total
				0.0-0.9	1.0-1.5	1.6-2.0	2+	
Scenario 1	behind	16 (high)	None	2 (7%)	5 (17%)	9 (31%)	13 (45%)	29
Scenario 2	behind	12 (low)	None	2 (6%)	4 (11%)	4 (11%)	26 (72%)	36
Scenario 3	behind	16 (high)	1 Ped	0 (0%)	0 (0%)	0 (0%)	17 (100%)	17
Scenario 4	behind	12 (low)	1 Ped	0 (0%)	0 (0%)	0 (0%)	4 (100%)	4
	Total			4 (4%)	9 (10%)	13 (14%)	66 (72%)	86

Table 10.5: Scenarios and number of traffic conflicts (PETs) in the field.

Field	Relative position of bicyclist	Bicyclist speed (mph)	Crossing ped	TTC (sec)				Total
				0.0-0.9	1.0-1.5	1.6-2.0	2+	
Scenario 1	behind	> 14 mph (high)	None	0 (0%)	1(10%)	0 (0%)	9 (90%)	10
Scenario 2	behind	< 14 mph (low)	None	0 (0%)	3 (10%)	4 (14%)	22 (76%)	29
Scenario 3	behind	> 14 mph (high)	1 Ped	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0
Scenario 4	behind	< 14 mph (low)	1 Ped	0 (0%)	0 (0%)	1 (25%)	3 (75%)	4
	Total			0 (0%)	4 (9%)	5 (12%)	34 (79%)	43

Inspection of the field observations show that only four observations were made when a pedestrian was present. No analysis can be conducted with these data points. The simulator setting was designed to expose drivers to the presence of a conflicting pedestrian in the crosswalk, whereas the volume of pedestrians was low in the field and drivers did not often conflict with a pedestrian.

Pooling the observations for high- and low-speed bicycles, a Chi-square test for goodness of fit was conducted to evaluate whether the field data show the expected distribution of driver behaviors. In order to execute a correct Chi-square approximation, the sample size of two groups (high risk, and moderate risk) that had small observations in the field were summed. The result indicated that the simulator and field-observed proportions were not significantly different (*p=0.184*). The sample size and cumulative percent of each group of observations are displayed in Figure 10.3. The sample size percentage of each group of observations is displayed within each respective bar in Figure 10.4.

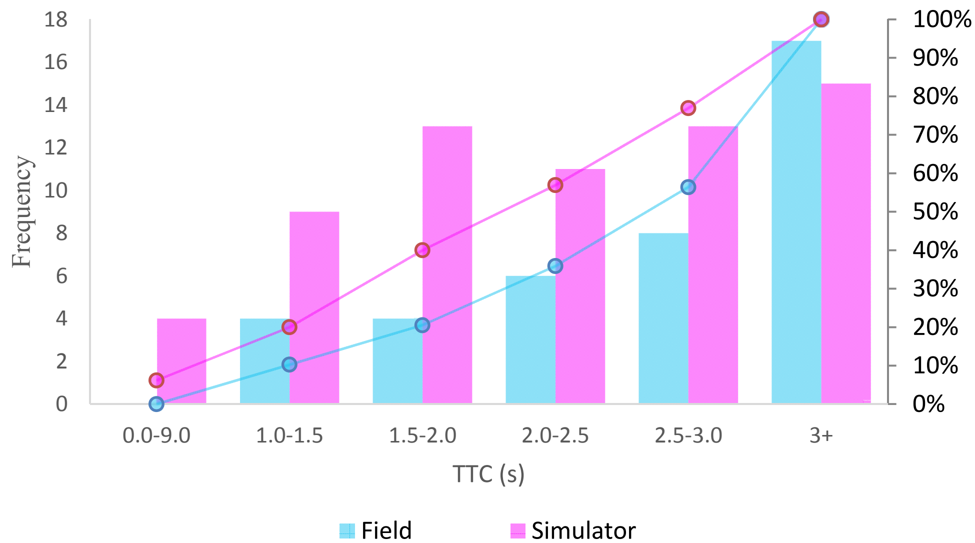


Figure 10.3: Frequency (left axis) and cumulative percent (right axis) of TTC values, no pedestrians, no oncoming traffic, high and low bicycle speeds.

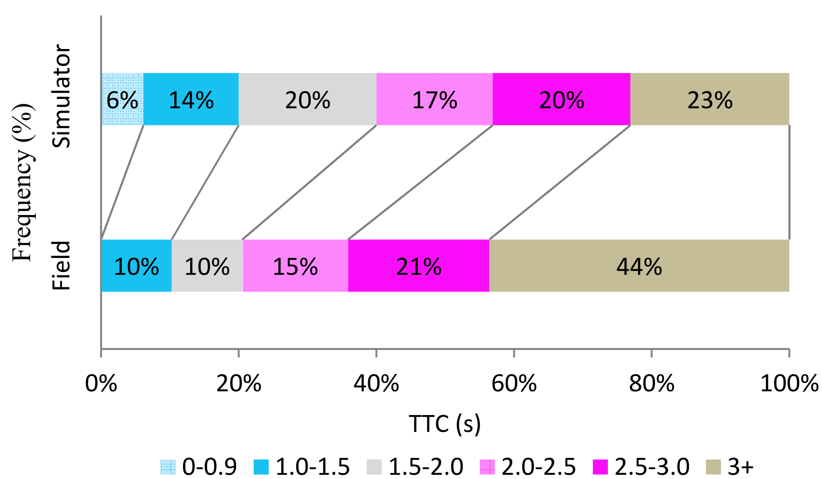


Figure 10.4: Distribution of PET/TTC values, no pedestrians, no oncoming traffic, high and low bicycle speeds.

The final comparison can be made by limiting the field observations to only the low-speed bicycles. A Chi-square test for goodness of fit was conducted to evaluate whether the field data show the expected distribution of driver behaviors. In order to execute a correct Chi-square approximation, the sample size of three groups (high risk, moderate risk, and low risk) that had small observations in the field were summed. The result indicated that the difference between the simulator and field-observed proportions was not significant ($p = 0.818$). The sample size and cumulative percentage of each group of observations are displayed in Figure 10.5. The sample size percentage of each group of observations is displayed within each respective bar in Figure 10.6.

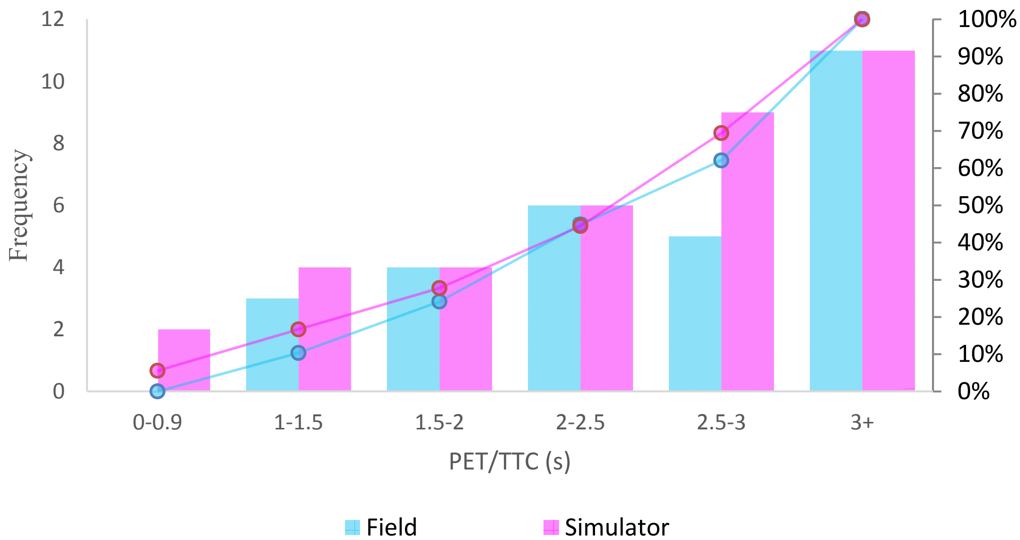


Figure 10.5: Frequency (left axis) and cumulative percent (right axis) of PET/TTC values, no pedestrians, no oncoming traffic, and low bicycle speeds.

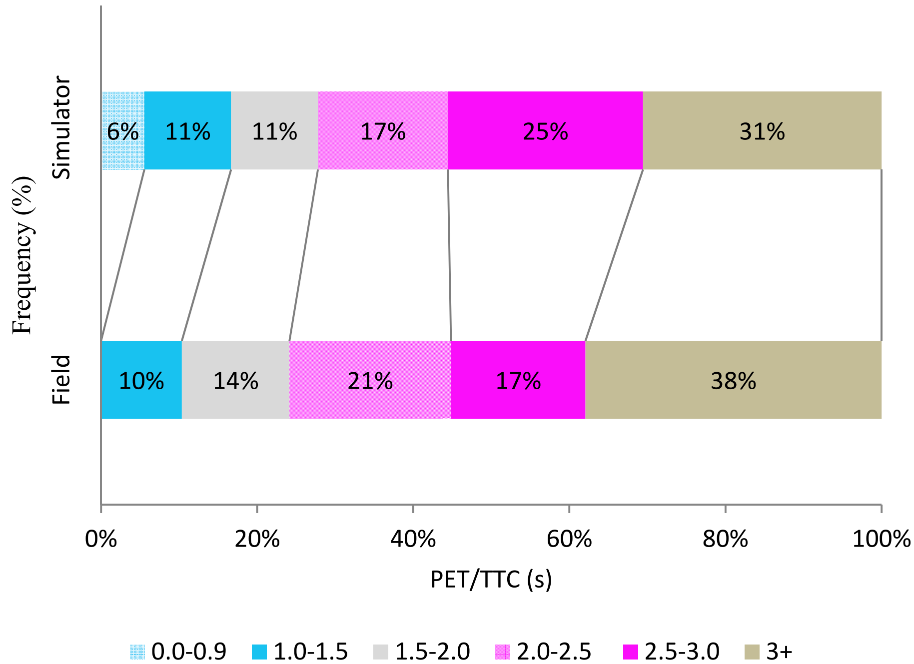


Figure 10.6: Distribution of PET/TTC values, no pedestrians, no oncoming traffic, low bicycle speeds.

10.4 SUMMARY

Few numbers of observations in the field, controlled versus uncontrolled situations, bicyclist speed, and on-coming, left-turning vehicular traffic were main different settings between the simulator and the field that would weaken the validity of the simulator. However, when we removed observations corresponding to these different settings, we obtained results indicating that the difference between the simulator and field-observed proportions was small (Table 10.6). We conclude that in the same environment, the driving simulator reflected the actual driving conditions, and the driver in the simulator had a real-world experience in the interaction with the bicyclist.

Table 10.6: Summary of comparisons of simulator and field observed conflicts.

	Comparison	Pedestrian in Crosswalk	Bicycle speed (mph)	Number of (TTCs/PETs)	P-value
Simulator **Field**	Each group of TTCs by Scenario 1 and 2	None None	Constant (12_{low},16_{high}) Variable($\leq 14_{low}$,$>14_{high}$)	65 39	0.1875
Simulator **Field**	By each group of TTCs	All All	All (constant) All (variable)	86 43	0.3653
Simulator **Field**	Each group of TTCs by Scenario 2	None None	Constant (12_{low}) Variable ($\leq 14_{low}$)	36 29	0.8184

11.0 RESULTS: EXPERIMENT 2 VISUAL ATTENTION

This chapter summarizes the analysis of the participants' eye-tracking data that were collected with a head-mounted optics eye tracker while driving through the 22 right-turning intersections in the simulated environment of Experiment 2. The primary objective of this experiment is to determine the effect of the selected engineering treatments on the likelihood of motorists scanning for the presence of bicyclists before turning right at a signalized intersection during the latter portion of the green phase. The chapter describes in more detail the experimental hypothesis for the visual attention component of the evaluation for Experiment 2.

11.1 DESCRIPTION OF EXPERIMENT 2

We hypothesized that right-turning motorists' visual search will be influenced by the 22 treatment combinations. Two hypotheses were formulated for each individual treatment:

- $H_{0\ (VSP1)}$: The engineering treatments have no effect on the right-turning motorists' mean total fixation duration on areas of interest in the driving environment.

- $H_{0\ (VSP2)}$: The engineering treatments have no effect on the proportion of motorists who fixate on an adjacent bicyclist during the right-turn maneuver at signalized intersections.

11.2 DESCRIPTIVE DATA ANALYSIS

Twenty-eight participants successfully completed the Experiment 2 driving simulator experiment. However, due to the eye-tracker calibration issues, 20 treatment intersections were lost across seven participants. As each treatment was only presented once to each participant, the rest of their data was still considered useable. This represents a total of 596 ([28*22]-20) right-turn maneuvers.

These data were reduced in a similar manner as the data from Experiment 1, as described in Chapter 7. Table 11.1 summarizes the Areas of Interest (AOIs) for Experiment 2. It is important to note that the "Bicyclist" AOI represents the bicyclist to the front of the vehicle or to the side of the vehicle (once the bicyclist is visible out the passenger side window), whereas the "Bicyclist in Side Mirror" AOI and "Bicyclist in Rear Mirror" AOI represent the bicyclist's presence behind the vehicle when the bicyclist is visible in the rear mirror and in the passenger side mirror. The "Side Mirror" AOI and "Rear Mirror" AOI represent the side and rear mirror, respectively, when there is no bike visible within them.

Figure 11.1 presents the distribution of participants that looked for the bicyclist in the side or rear mirror across all 596 right-turn maneuvers. The participants were considered to have looked for the bicyclist if at least one of the following variables was greater than zero ("Side Mirror," "Rear Mirror," "Bicyclist in Side Mirror," or "Bicyclist in Rear Mirror"). Of the 596 right-turn maneuvers, 470 maneuvers (79%) involved participants looking for the bicyclist and 126 maneuvers (21%) did not involve participants looking for the bike.

Table 11.2 summarizes the average total fixation durations (ATFDs) of all of the AOIs, collected at the 22 right-turn experimental intersections.

Table 11.1: Summary of areas of interest.

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

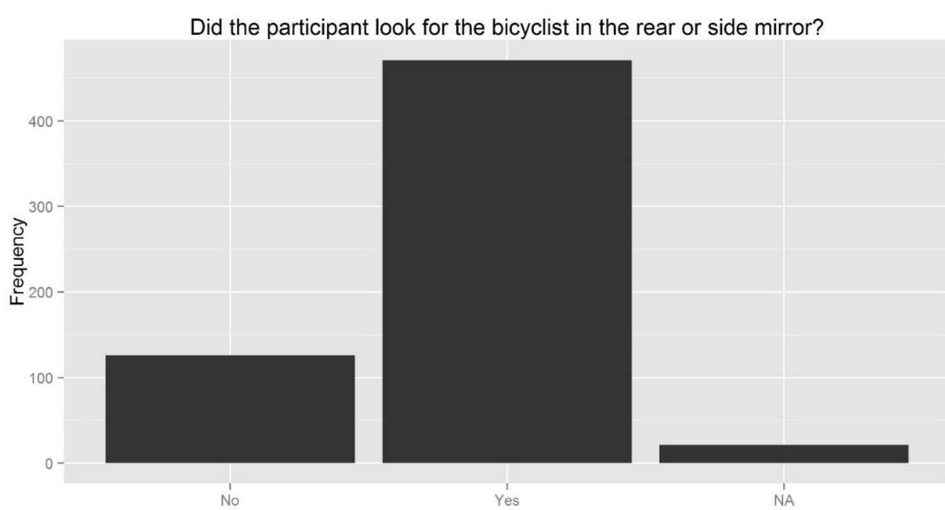


Figure 11.1: Distribution of participants that looked the bicyclist in the rear or side mirror, across all 616 right-turn maneuvers

Table 11.2: Summary of AOI Average Total Fixation Durations (ATFD) (sec) by treatment number

T #	ATFD (sec)										
	Bicyclist in SideMirror	Bicyclist in RearMirror	Bicyclist	SideMirror	RearMirror	Turning Vehicle	Signal	Pavement Marking	Signage	Protected Intersection Pavement Marking	Protected Intersection Island
1	0.28	0.15	0.09	0.33	0.47	1.90	0.72	-	-	-	-
2	0.19	0.04	0.10	0.15	0.32	2.32	0.58	0.81	-	-	-
3	0.30	0.11	0.12	0.25	0.40	1.99	0.73	0.64	-	-	-
4	0.30	0.24	0.14	0.21	0.45	1.68	0.37	1.06	-	-	-
5	0.16	0.12	0.11	0.23	0.46	1.72	0.65	1.16	-	-	-
6	0.14	0.19	0.08	0.21	0.32	1.83	0.79	-	-	-	-
7	0.38	0.19	0.13	0.23	0.35	2.29	0.52	0.66	-	-	-
8	0.32	0.15	0.16	0.23	0.24	2.09	0.81	0.87	-	-	-
9	0.14	0.09	0.13	0.25	0.24	1.99	0.42	1.47	-	-	-
10	0.05	0.25	0.12	0.19	0.28	2.25	0.77	1.17	-	-	-
11	0.20	0.20	0.14	0.33	0.19	1.80	0.72	-	0.76	-	-
12	0.25	0.16	0.12	0.23	0.37	1.59	0.77	0.47	0.90	-	-
13	0.25	0.17	0.14	0.42	0.34	1.61	0.56	0.73	0.69	-	-
14	0.25	0.11	0.26	0.26	0.31	1.58	0.45	1.18	1.02	-	-
15	0.27	0.12	0.23	0.27	0.28	1.61	0.51	1.13	0.63	-	-
16	0.29	0.15	0.20	0.18	0.27	1.87	0.93	-	0.73	-	-
17	0.22	0.10	0.11	0.23	0.36	2.26	0.69	0.58	0.99	-	-
18	0.18	0.19	0.14	0.17	0.25	1.51	0.58	0.94	0.68	-	-
19	0.25	0.21	0.23	0.22	0.36	1.80	0.52	1.47	0.79	-	-
20	0.22	0.13	0.23	0.29	0.25	1.49	0.81	1.29	0.85	-	-
21	0.07	0.16	0.38	0.25	0.38	2.29	0.69	-	-	-	1.41
22	0.15	0.09	0.24	0.16	0.27	1.31	0.46	-	1.38	1.12	0.92

Note: "-" within table means that the AOI is not presented in that grid.

Figure 11.2 shows the ATFD values and 95% confidence intervals (CIs) for all participants, specifically for seven AOIs at an intersection scenario where the motorist was presented with an intersection with the level zero signage treatment, the level zero pavement marking treatment, the level zero curb radii treatment, and the level zero protected intersection treatment (S0, PM0, C0, and PI0). This particular intersection is the most basic of all intersections shown to the participants. Note that the driver allocates the highest portion of their visual attention to the turning vehicle.

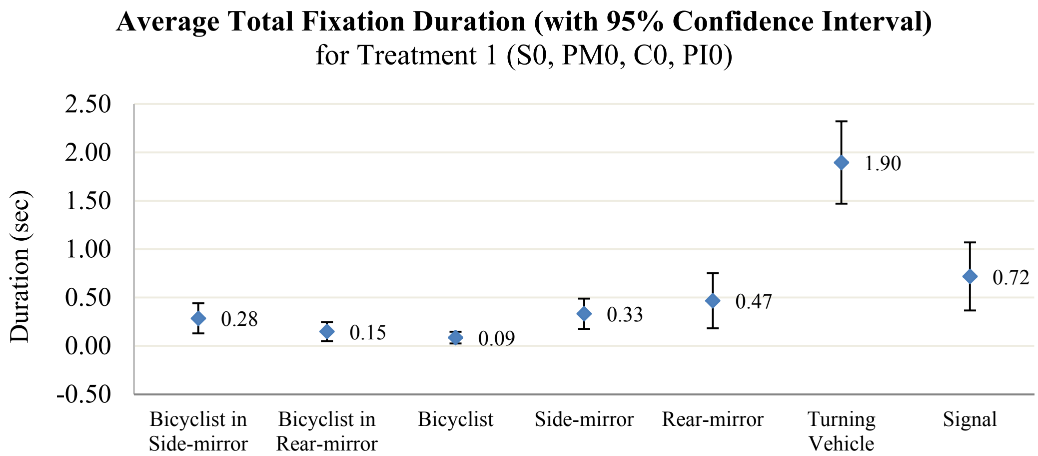


Figure 11.2: ATFDs with 95% CIs for control case (S0, PM0, C0, and PI0)

Figure 11.3 shows the ATFD values and 95% CIs for all participants, specifically for seven AOIs at an intersection scenario where the treatments included the level one signage treatment, the level zero curb radii treatment, and the level two protected intersection treatment (S1, C0, and PI2). This case includes one of the highest levels of treatment, when compared to the control intersection.

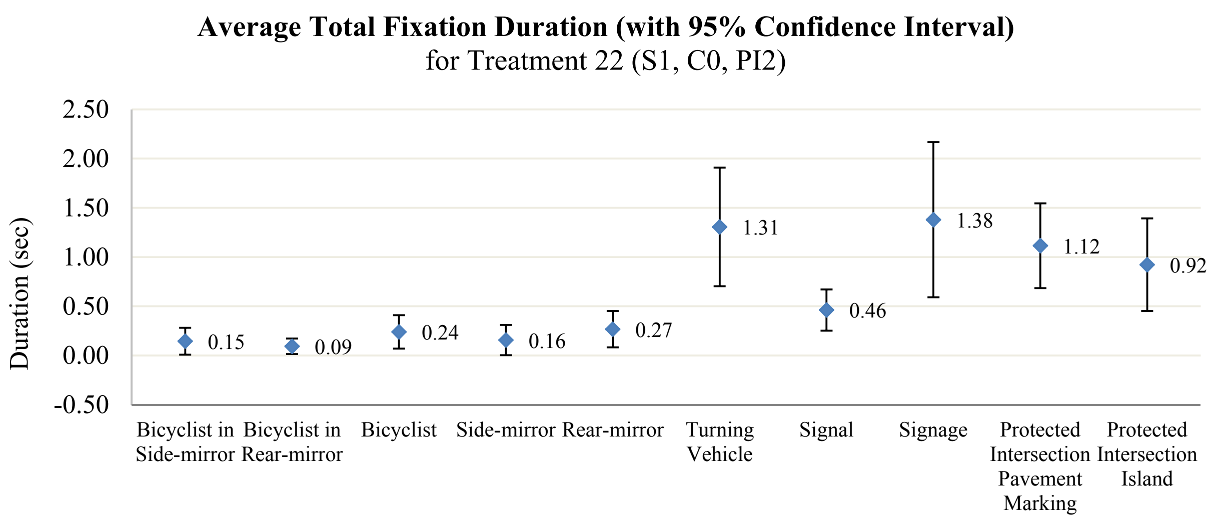


Figure 11.3: ATFD with 95% CIs for one of the highest levels of treatment (S1, C0, and PI2)

11.3 STATISTICAL ANALYSIS

The presence of the engineering treatments may influence motorists' visual attention while turning right. Therefore, all the treatment factors were included as independent variables. It should be noted that although other factors, such as motorists' experience level and age or conspicuity of the bicyclist may also influence motorist visual search task at an intersection, those factors are outside the scope of this study.

The primary dependent variable of this experiment was the visual attention of motorists during the right-turn maneuver at signalized intersections. Average total fixation duration (ATFD) was documented for each AOI as it provided a quantitative measure of how motorist visual attention was distributed across targets *(Fisher et al. 2011).* Fixation data for different AOIs were statistically analyzed to answer the research hypotheses using Excel and R statistical software.

11.3.1 **Effect of Engineering Treatments on Average Total Fixation Duration**

To answer the first research hypothesis ($H_{0\ (VSP1)}$) regarding the treatments, the dataset was split by the four independent treatment variables: 1) signage, 2) pavement markings, 3) curb radii, and 4) protected intersections. The dataset was aggregated this way to isolate the impact of individual variable levels.

11.3.1.1 Signage Treatments

Figure 11.4 shows the ATFDs with 95% CIs on the 11 AOIs for the signage treatment variable levels: S0= no signage present, and S1= signage present.

The graphical comparison shows that while most of the ATFDs remain the same with the level one signage treatment, the ATFDs for the "Side Mirror" and the "Bicyclist in Side Mirror" AOIs increase with the level one signage treatment. This finding suggests that when the level one signage treatment is present, drivers spend more time scanning for the bicyclist in the side mirror as compared to the level zero signage treatment (0.23 sec vs 0.21 sec, a 9% increase, and 0.25 second vs 0.23 second, 10% increase, respectively). This indicates that the level one signage treatment may positively influence the 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 level one signage treatment is present. The driver is already looking in that direction, so it may feel natural to simply continue moving the scan path to the right, towards the passenger side mirror. This would also explain the reduction in the ATFD for the "Rear Mirror" AOI with the presence of the additional signage (0.30 sec vs. 0.35 sec, a 14% decrease).

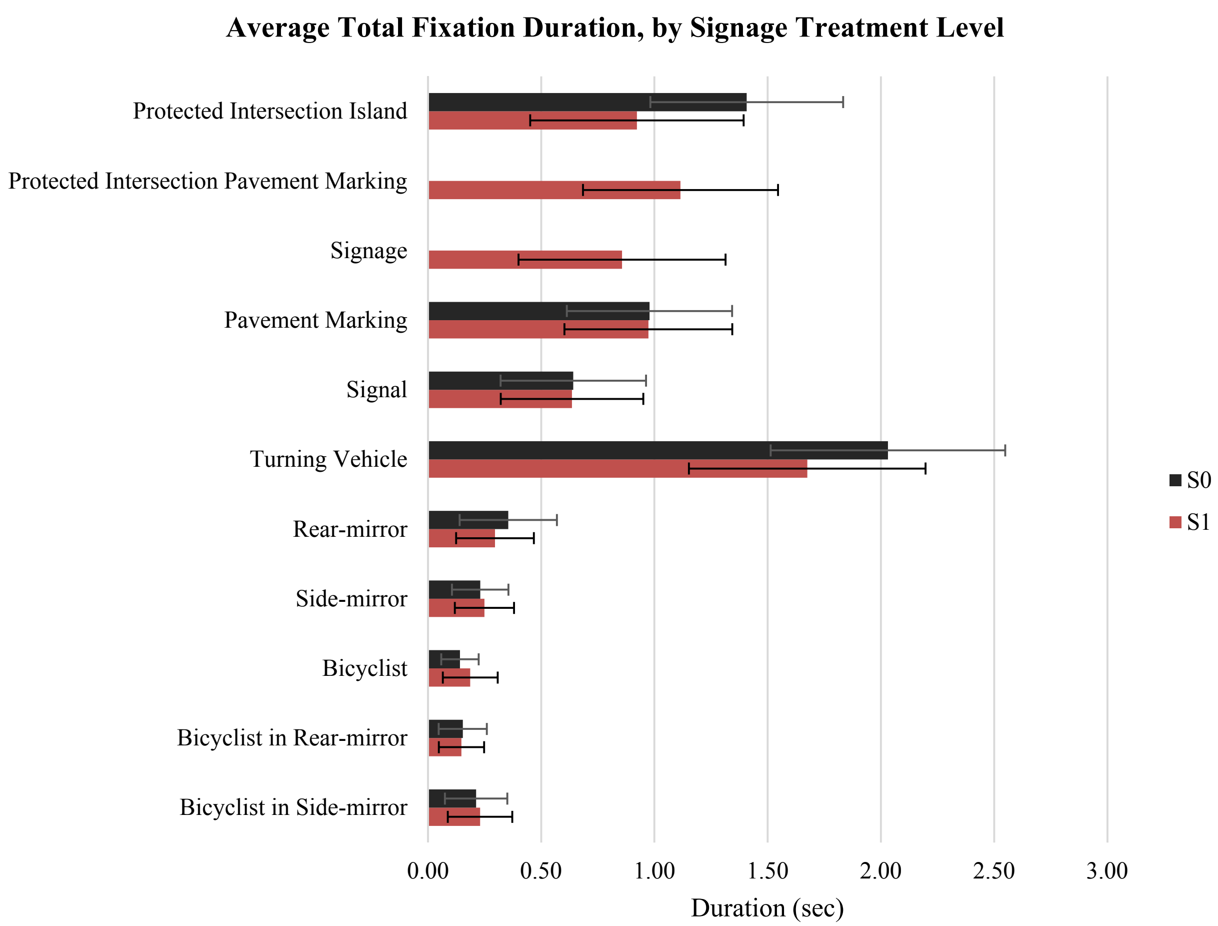


Figure 11.4: Bar plots of ATFD (sec) for the signage treatment levels
(S0= no signage present, and S1= signage present)

A two-sample Welch's t-test was performed for all of the AOIs of interest, with respect to the level zero signage treatment (S0) and level one signage treatment (S1). These tests compared the ATFDs for the S0 condition to the ATFDs for the S1 condition to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for S0 and S1. Table 11.3 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were strongly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that the only statistically significant difference in ATFDs occurred for the "Turning Vehicle" AOI, with a two-tailed p-value of 0.001 for the comparison between S0 and S1. When the level one signage treatment was present, the motorists spent less time fixating on the oncoming turning vehicles in comparison to the level zero signage treatment (1.85 sec vs 2.16 sec). This change could influence the ATFDs for the bike-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. The ANOVA analysis also showed that fixations on the oncoming turning vehicles had statistically significant differences as measured by ATFDs, with a p-value of 0.001. No other significant differences were found with 95% confidence.

Table 11.3: Statistical analysis of difference in ATFDs by signage treatment level

Areas of Interest	**Signage Treatment Levels**		**ANOVA**	**Welch's Two sample two tail *t*-test**		
	S0	**S1**		**S0 vs. S1**		
	ATFD (sec)		**p-value**	**p-value**	**Sig**	**Diff**
Bicyclist in Side Mirror	0.63	0.57	0.46	0.46	No	-0.06
Bicyclist in Rear Mirror	0.50	0.42	0.07	0.07	No	-0.08
Bicyclist	0.35	0.42	0.31	0.31	No	0.07
Side Mirror	0.48	0.48	0.88	0.88	No	0.00
Rear Mirror	0.63	0.56	0.66	0.66	No	-0.07
Turning Vehicle	**2.16**	**1.85**	**0.001***	**0.001***	**Yes**	**-0.31**
Signal	0.98	0.94	0.53	0.53	No	-0.04
Pavement Marking	1.21	1.18	0.42	0.42	No	0.03
Protected Intersection Island	0.62	1.07	0.13	0.13	No	0.45

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

11.3.1.2 Pavement Marking Treatments

Figure 11.5 shows the ATFDs with 95% CIs on the nine AOIs for the pavement marking treatment variable levels: PM0= no pavement marking; PM1= a single, dotted white bike line with stencil; PM2= a double, dotted white bike line with stencil; PM3= a skipped green bike lane with white outline; and PM4= a solid green bike lane with dotted white outline.

This figure doesn't provide a clear indication as to which pavement marking level provides the best improvements in ATFD. A treatment may increase for one AOI but decrease for another. For this reason, the figures and analyses for the pavement marking levels have been further divided into four groups to separately compare the level zero pavement marking treatment against the other four treatments levels: 1) PM0 & PM1, 2) PM0 & PM2, 3) PM0 & PM3, and 4) PM0 & PM4.

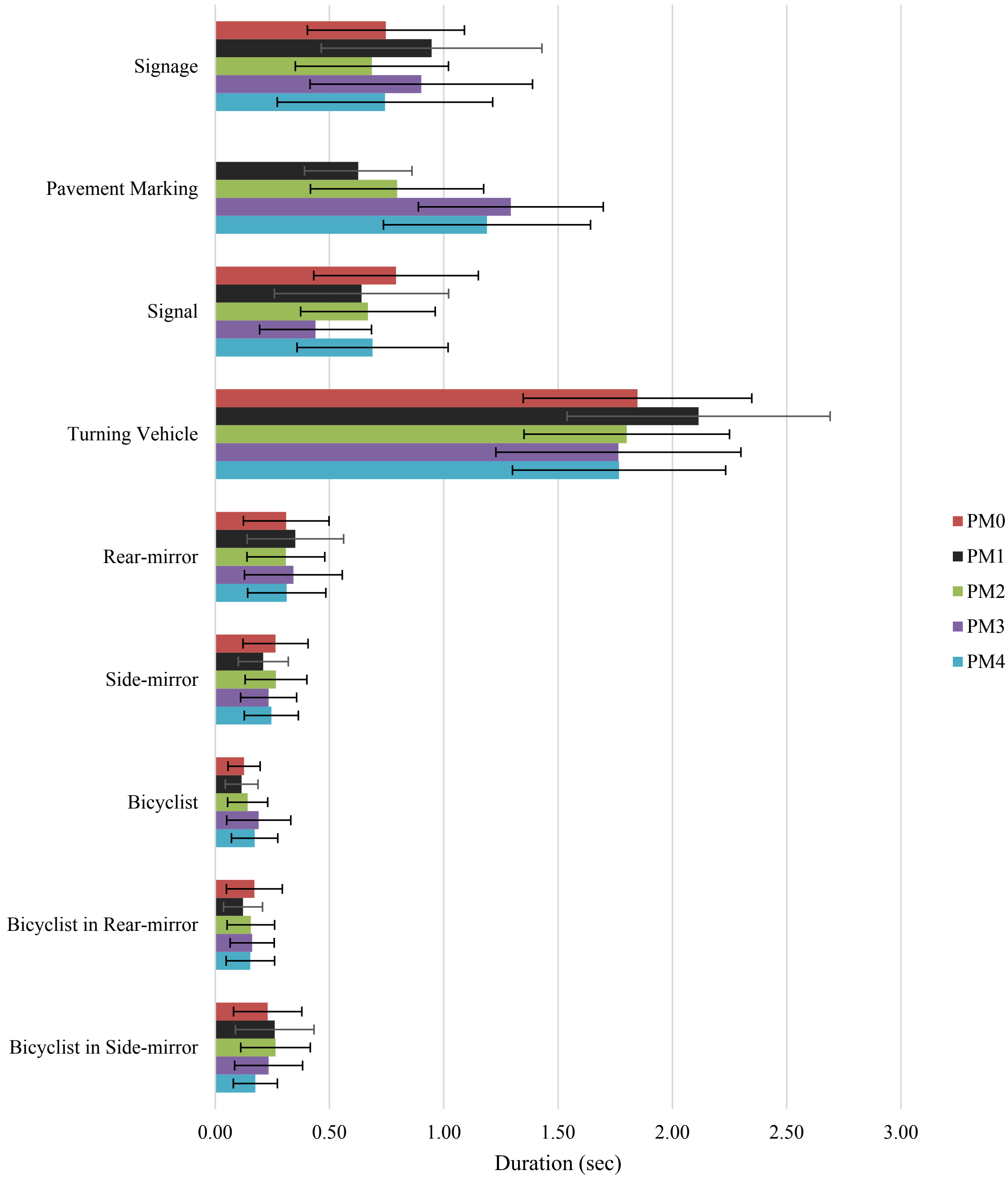


Figure 11.5: Bar plots of ATFD (s) for the pavement marking treatment levels (PM0= no pavement marking, PM1= single, dotted white bike line with stencil, PM2= double, dotted white bike line with stencil, PM3= skipped green bike lane with white outline, and PM4= solid green bike lane with dotted white outline)

PM0 and PM1

Figure 11.6 shows the ATFDs with 95% CIs on the nine AOIs for the following pavement marking treatment variable levels: PM0= no pavement marking, and PM1= a single, dotted white bike line with stencil.

The graphical comparison shows no consistent pattern of change between the ATFDs for level zero pavement marking treatment (PM0) and those of the level one pavement marking treatment (PM1). The ATFDs for the following AOIs decreased for PM1: “Signal,” “Side Mirror,” “Bicyclist,” and “Bicyclist in Rear Mirror.” These findings suggest that when the level one pavement marking treatment is present drivers spend less time scanning for the bicyclist in the side mirror (0.31 sec vs 0.35 sec, an 11% decrease) on the approach to the intersection, and less time scanning for the bicyclist in the rear mirror in the closer vicinity to the intersection (0.12 sec vs 0.13 sec, an 8% decrease), as compared to the level zero pavement marking treatment level.

While the ATFDs for these AOIs decreased, the ATFDs for the following AOIs increased for PM1: “Signage,” “Turning Vehicle,” “Rear Mirror,” and “Bicyclist in Side Mirror.” These findings suggest that when the level one pavement marking treatment is present, drivers spend more time scanning for the bicyclist in the rear mirror (0.35 sec vs 0.31 sec, a 13% increase) on the approach to the intersection, and more time scanning for the bicyclist in the side mirror in the closer vicinity to the intersection (0.26 sec vs 0.23 sec, a 13% increase), as compared to the level zero pavement marking treatment.

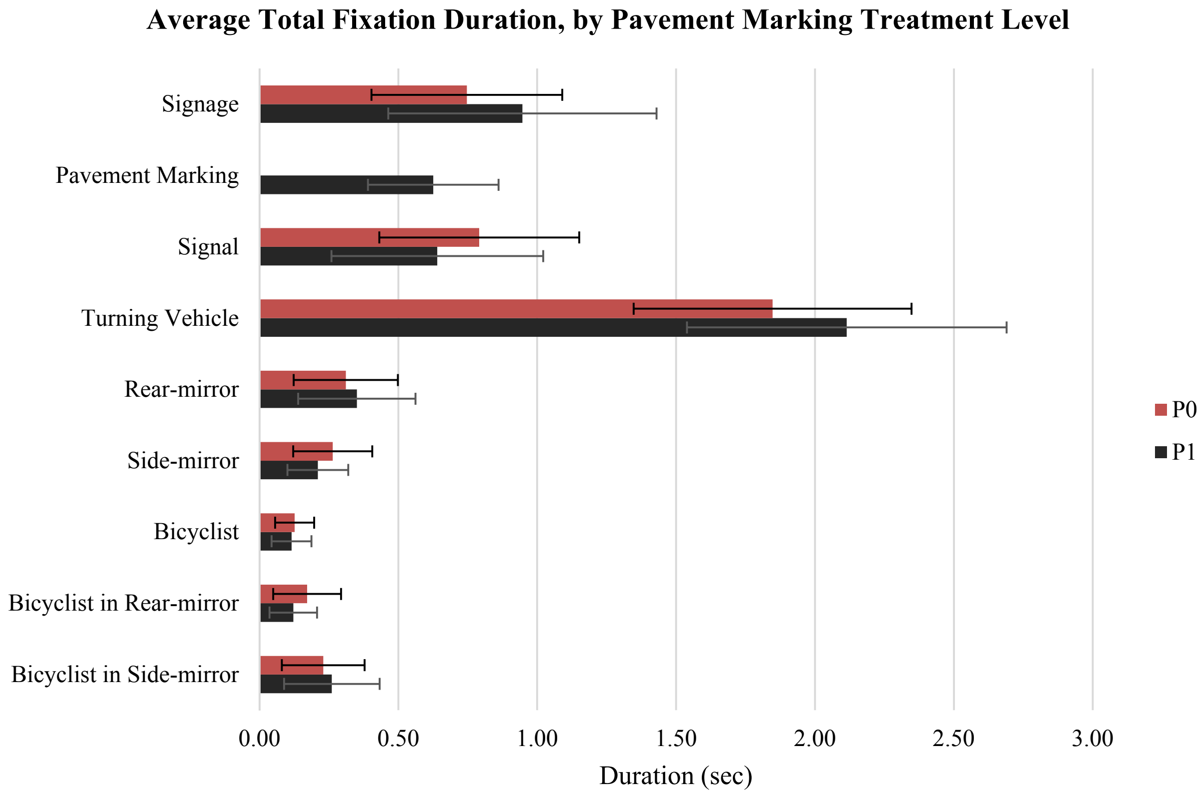


Figure 11.6: Bar plots of ATFD (s) for the group 1 pavement marking treatment levels (PM0= no pavement marking, and PM1= a single, dotted white bike line with stencil)

A two-sample Welch's t-test was performed for all of the AOIs, with respect to PM0 and PM1. These tests compared the ATFDs for PM0 and PM1 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PM0 and PM1. Table 11.4 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that the only statistically significant difference in ATFDs for PM0 and PM1 occurred for the "Signal" AOI, with a two-tailed p-value of 0.01. When the level one pavement marking treatment was present, the motorists spent less time fixating on the traffic signal, in comparison to the level zero pavement marking treatment (0.93 sec vs 1.15 sec). This change may influence the ATFDs for the bike-related AOIs in that a greater portion of their visual attention can now be allocated to the

ATFDs for those bike-related AOIs. The ANOVA analysis did not result in any statistically significant differences as measured by ATFDs. No other significant differences were found with 95% confidence.

Table 11.4: Statistical analysis of difference in ATFDs by pavement marking treatment level

Areas of Interest	Pavement Marking Treatment Levels		ANOVA	Welch's Two sample two tail *t*-test		
	PM0	PM1		PM0 vs. PM1		
	ATFD (sec)		p-value	p-value	Sig	Diff
Bicyclist in Side Mirror	0.64	0.75	0.37	0.37	No	0.11
Bicyclist in Rear Mirror	0.48	0.42	0.96	0.96	No	-0.06
Bicyclist	0.31	0.31	0.89	0.89	No	0.00
Side Mirror	0.55	0.41	0.07	0.07	No	-0.06
Rear Mirror	0.58	0.68	0.28	0.28	No	0.10
Turning Vehicle	2.01	2.23	0.57	0.57	No	0.22
Signal	**1.15**	**0.93**	**0.01***	**0.01***	**Yes**	**0.22**
Signage	1.07	1.31	0.49	0.49	No	0.24

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

PM0 and PM2

Figure 11.7 shows the ATFDs with 95% CIs on the nine AOIs for the following pavement marking treatment variable levels: PM0= no pavement marking, and PM2= a double, dotted white bike line with stencil.

The graphical comparison shows no consistent pattern of change between the ATFDs for the level zero pavement marking treatment (PM0) and the level two pavement marking treatment (PM2). The ATFDs for the following AOIs decreased for PM2: “Signage,” “Signal,” “Turning Vehicle,” and “Bicyclist in Rear Mirror.” These findings suggest that when the level two pavement marking treatment is present, drivers spend less time scanning for the bicyclist in the rear mirror in close vicinity to the intersection compared to the level zero pavement marking treatment (0.16 sec vs 0.17 sec, a 6% decrease).

While the ATFDs for these AOIs decreased, the ATFDs for the following AOIs increased for PM2: “Bicyclist,” and “Bicyclist in Side Mirror.” These findings suggest that when the level two pavement marking treatment is present, drivers spend more time scanning for the bicyclist in the side mirror in close vicinity to the intersection (0.26 sec vs 0.23 sec, a 13% increase), compared to the level zero pavement marking treatment.

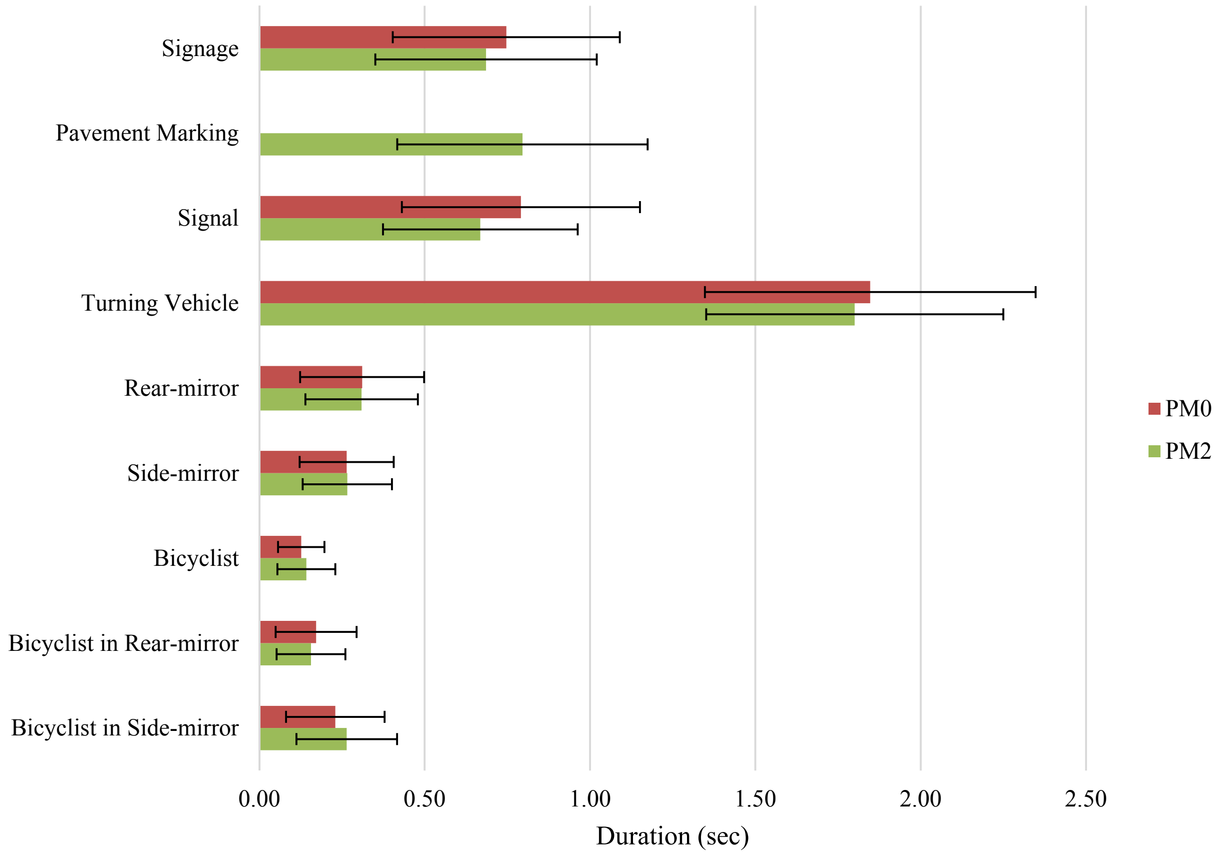


Figure 11.7: Bar plots of ATFD (s) for the group 2 pavement marking treatment levels (PM0= no pavement marking, and PM2= a double, dotted white bike line with stencil)

A two-sample Welch's t-test was performed for all of the AOIs, with respect to the no additional pavement marking treatment level (PM0) and the second additional pavement marking treatment level (PM2). These tests compared the ATFDs for the PM0 condition to the ATFDs for the PM2 condition to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PM0 and PM2. Table 11.5 presents the results of these two tests.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test and the ANOVA analysis did not result in any statistically significant differences between PM0 and PM2, as measured by ATFDs, with 95% confidence.

Table 11.5: Statistical analysis of difference in ATFDs by pavement marking treatment level

Areas of Interest	Pavement Marking Treatment Levels		ANOVA	Welch's Two sample two tail t-test		
	PM0	PM2		PM0 vs. PM2		
	ATFD (sec)		p-value	p-value	Sig	Diff
Bicyclist in Side Mirror	0.64	0.62	0.85	0.85	No	-0.02
Bicyclist in Rear Mirror	0.48	0.42	0.79	0.79	No	-0.06
Bicyclist	0.31	0.35	0.53	0.53	No	0.04
Side Mirror	0.55	0.51	0.44	0.44	No	-0.04
Rear Mirror	0.58	0.50	0.63	0.63	No	-0.08
Turning Vehicle	2.01	1.93	0.79	0.79	No	-0.08
Signal	1.15	0.94	0.15	0.15	No	-0.21
Signage	1.07	1.10	0.54	0.54	No	0.03

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

PM0 and PM3

Figure 11.8 shows the ATFDs with 95% CIs on the nine AOIs for the following pavement marking treatment variable levels: PM0= no pavement marking, and PM3= a skipped green bike lane with white outline.

The graphical comparison shows no consistent pattern of change between the ATFDs for the level zero pavement marking treatment (PM0) and those of the level three pavement marking treatment (PM3). The ATFDs for the following AOIs decreased for PM3: "Signal," "Turning Vehicle," "Side Mirror," and "Bicyclist in Rear Mirror." These findings suggest that when the level three pavement marking treatment is present, drivers spend less time scanning for the bicyclist in the side mirror on the approach (0.23 sec vs 0.26 sec, a 12% decrease), and less time scanning for the bicyclist in the rear mirror in close vicinity to the intersection (0.16 sec vs. 0.17, a 6% decrease), compared to the level zero pavement marking treatment.

While the ATFDs for these AOIs decreased, the ATFDs for the following AOIs increased for PM3: "Signage," "Rear Mirror," and "Bicyclist." These findings suggest that when the level three pavement marking treatment is present, drivers spend more time scanning for the bicyclist in the rear mirror on the approach to the intersection, compared to the level zero pavement marking treatment (0.34 sec vs 0.31 sec, a 10% increase).

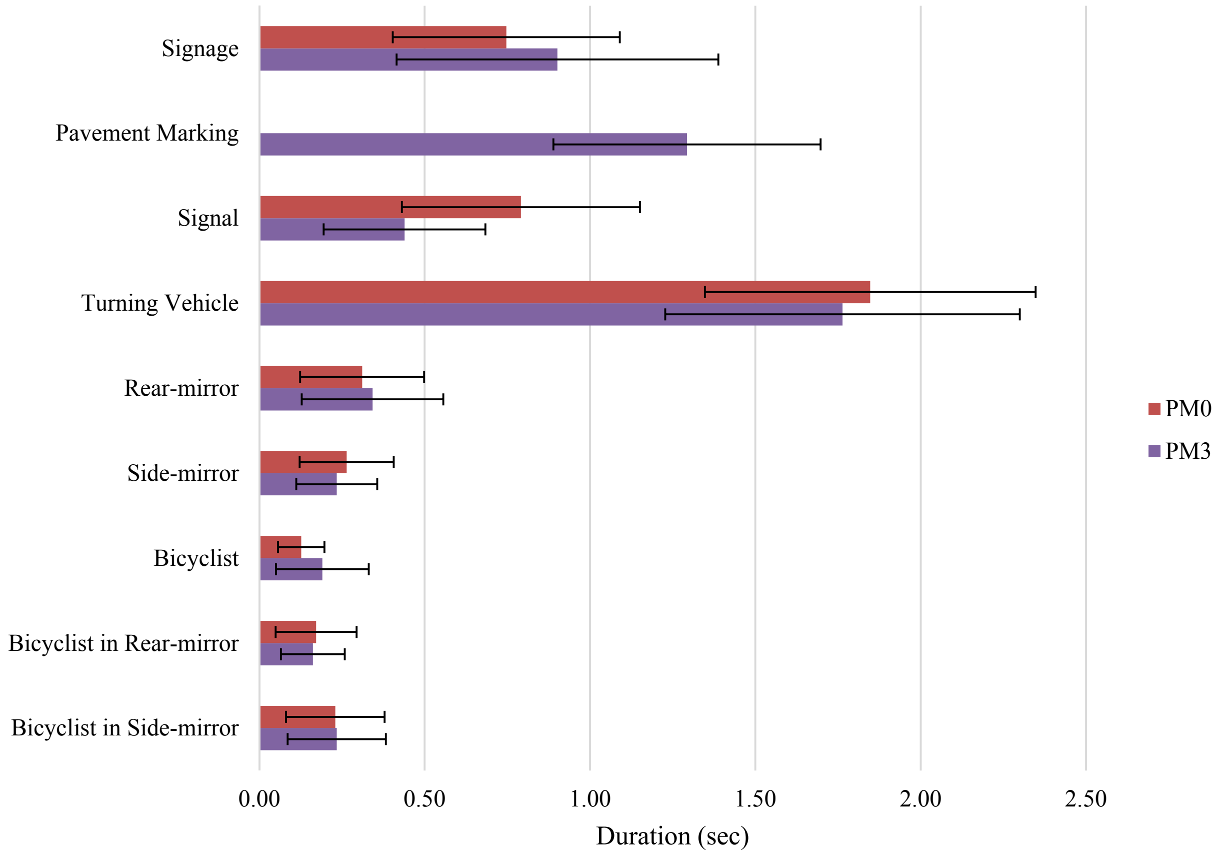


Figure 11.8: Bar plots of ATFD (s) for the group 3 pavement marking treatment levels (PM0= no pavement marking, and PM3= skipped green bike lane with white outline)

A two-sample Welch's t-test was performed for all of the AOIs, with respect to the level zero pavement marking treatment (PM0) and the level three pavement marking treatment (PM3). These tests compared the ATFDs for PM0 and PM3 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PM0 and PM3. Table 11.6 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that the only statistically significant difference in ATFDs for PM0 and PM3 occurred for the "Signal" AOI, with a two-tailed p-value of 0.001. This finding suggests that when the level three pavement marking treatment is present, the motorists spend less time fixating on the traffic signal in comparison to the level zero pavement marking treatment (0.72 sec vs 1.15 sec). The ANOVA analysis also showed that fixations on the traffic signal had a statistically significant difference, as measured by ATFDs, with a p-value of 0.001. No other significant differences were found with 95% confidence.

Table 11.6: Statistical analysis of difference in ATFDs by pavement marking treatment level

Areas of Interest	Pavement Marking Treatment Levels		ANOVA	Welch's Two sample two tail *t*-test		
	PM0	PM3		PM0 vs. PM3		
	ATFD (sec)		p-value	p-value	Sig	Diff
Bicyclist in Side Mirror	0.64	0.60	0.43	0.43	No	-0.04
Bicyclist in Rear Mirror	0.48	0.40	0.56	0.56	No	-0.08
Bicyclist	0.31	0.44	0.23	0.23	No	0.13
Side Mirror	0.55	0.46	0.28	0.28	No	-0.09
Rear Mirror	0.58	0.68	0.09	0.09	No	0.10
Turning Vehicle	2.01	1.92	0.47	0.47	No	-0.09
Signal	**1.15**	**0.72**	**0.001***	**0.001***	**Yes**	**-0.43**
Signage	1.07	1.34	0.50	0.50	Yes	0.27

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

PM0 and PM4

Figure 11.9 shows the ATFDs with 95% CIs on the nine AOIs for the following pavement marking treatment variable levels: PM0= no pavement marking, and PM4= a solid green bike lane with dotted white outline.

The graphical comparison shows no consistent pattern of change between the ATFDs for the level zero pavement marking treatment and those of the level four pavement marking treatment. The ATFDs for the following AOIs decreased for PM4: "Signage," "Signal," "Turning Vehicle," "Side Mirror," "Bicyclist in Rear Mirror," and "Bicyclist in Side Mirror." These findings suggest that when the level four pavement marking treatment is present, drivers spend less time scanning for the bicyclist in the side mirror on the approach (0.25 sec vs 0.26 sec, a 4% decrease), and less time scanning for the bicyclist in the rear and side mirror in close vicinity to the intersection (0.15 sec vs. 0.17, a 12% decrease, and 0.18 sec vs. 0.23 sec, a 22% decrease, respectively), as compared to the level zero pavement marking treatment.

While the ATFDs for these AOIs decreased, the ATFDs for the "Bicyclist" AOI increased for PM4. This is not significant to the motorist scanning for the bicyclist because the bicyclist is adjacent to or has already passed the vehicle when the "Bicyclist" AOI is visible.

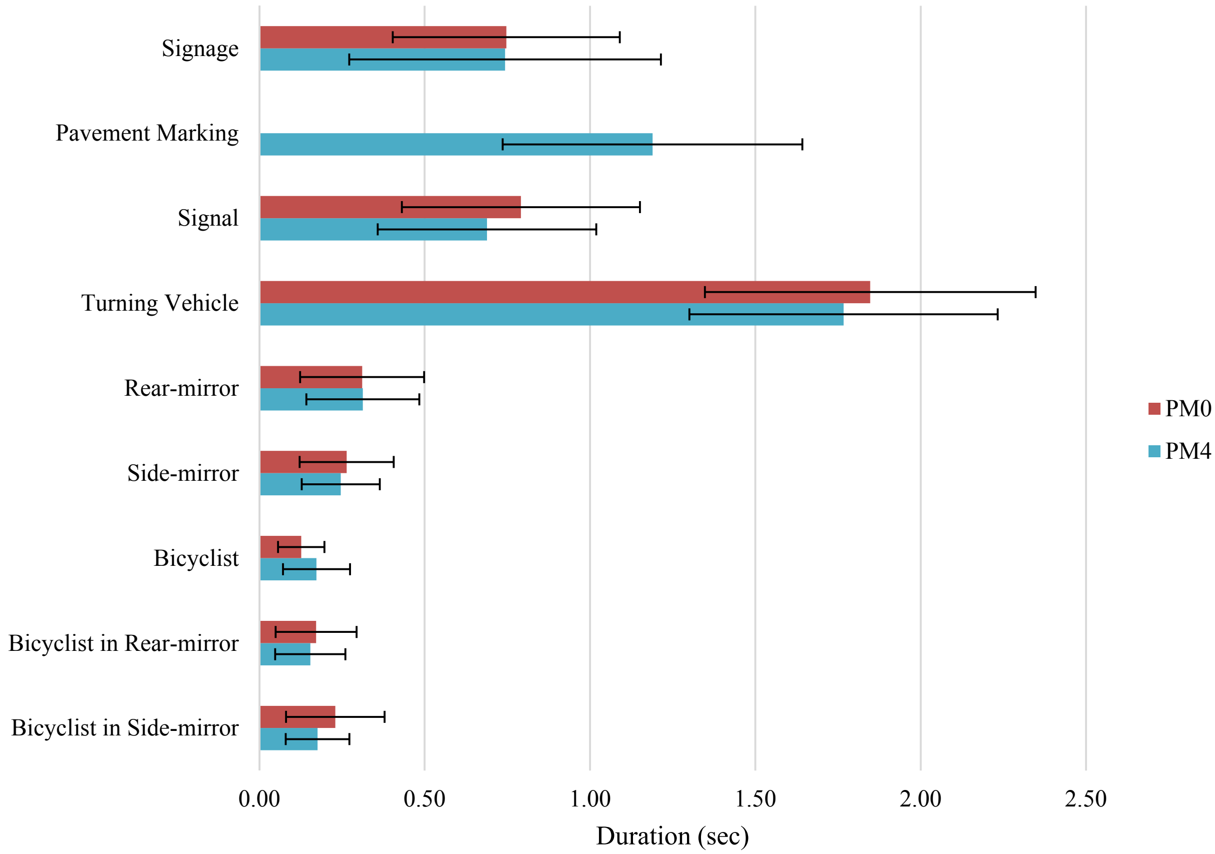


Figure 11.9: Bar plots of ATFD (s) for the group 4 pavement marking treatment levels (PM0= no pavement marking, and PM4= solid green bike lane with dotted white outline)

A two-sample Welch's t-test was performed for all of the AOIs, with respect to the level zero pavement marking treatment (PM0) and the level four pavement marking treatment (PM4). These tests compared the ATFDs for PM0 and PM4 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PM0 and PM4. Table 11.7 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that the only statistically significant difference in ATFDs for PM0 and PM4 occurred for the "Bicyclist in Side Mirror" AOI, with a two-tailed p-value of 0.03. This finding suggests that when the level four pavement marking treatment is present, the motorists spent less time fixating on the bicyclist in the side mirror in close proximity to the intersection, in comparison to the level zero pavement marking treatment (0.45 sec vs 0.62 sec). The ANOVA analysis also showed that fixations on the traffic signal had a statistically significant difference, as measured by ATFDs, with a p-value of 0.03. No other significant differences were found with 95% confidence.

Table 11.7: Statistical analysis of difference in ATFDs by pavement marking treatment level

Areas of Interest	Pavement Marking Treatment Levels		ANOVA	Welch's Two sample two tail *t*-test		
	PM0	PM4		PM0 vs. PM4		
	ATFD (sec)		p-value	p-value	Sig	Diff
Bicyclist in Side Mirror	**0.64**	**0.45**	**0.03***	**0.03***	**Yes**	**-0.19**
Bicyclist in Rear Mirror	0.48	0.53	0.30	0.30	No	0.05
Bicyclist	0.31	0.39	0.35	0.35	No	0.08
Side Mirror	0.55	0.47	0.33	0.33	No	-0.08
Rear Mirror	0.58	0.58	0.64	0.64	No	0.00
Turning Vehicle	2.01	1.92	0.75	0.75	No	0.09
Signal	1.15	1.01	0.21	0.21	No	0.14
Signage	1.07	1.17	0.94	0.94	No	0.16

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

11.3.1.3 Curb Radii Treatments

Figure 7.5 shows the ATFDs with 95% CIs on the 11 AOIs for the following curb radii treatment variable levels: C0= 30ft curb radii and C1= 10 foot curb radii.

The graphical comparison shows no consistent pattern of change between the ATFDs for the level zero curb radii treatment (C0) and those of the level one curb radii treatment (C1). The ATFDs for the following AOIs decreased for C1: "Signage," "Rear Mirror," "Side Mirror," and "Bicyclist." These findings suggest that when the level one curb radii treatment is present, drivers spend less time scanning for the bicyclist in the rear and side mirror on the approach to the intersection, compared to the level zero curb radii treatment (0.29 sec vs. 0.35 sec, a 17% decrease, and 0.22 sec vs. 0.26 sec, a 15% decrease, respectively).

While the ATFDs for these AOIs decreased, the ATFDs for the following AOIs increased for C1: "Pavement Marking," "Signal," "Turning Vehicle," and "Bicyclist in Rear Mirror." These findings suggest that when the level one curb radii treatment is present, drivers spend more time scanning for the bicyclist in the rear mirror in close proximity to the intersection, compared to the level zero curb radii treatment (0.16 sec vs. 0.14 sec, a 14% increase).

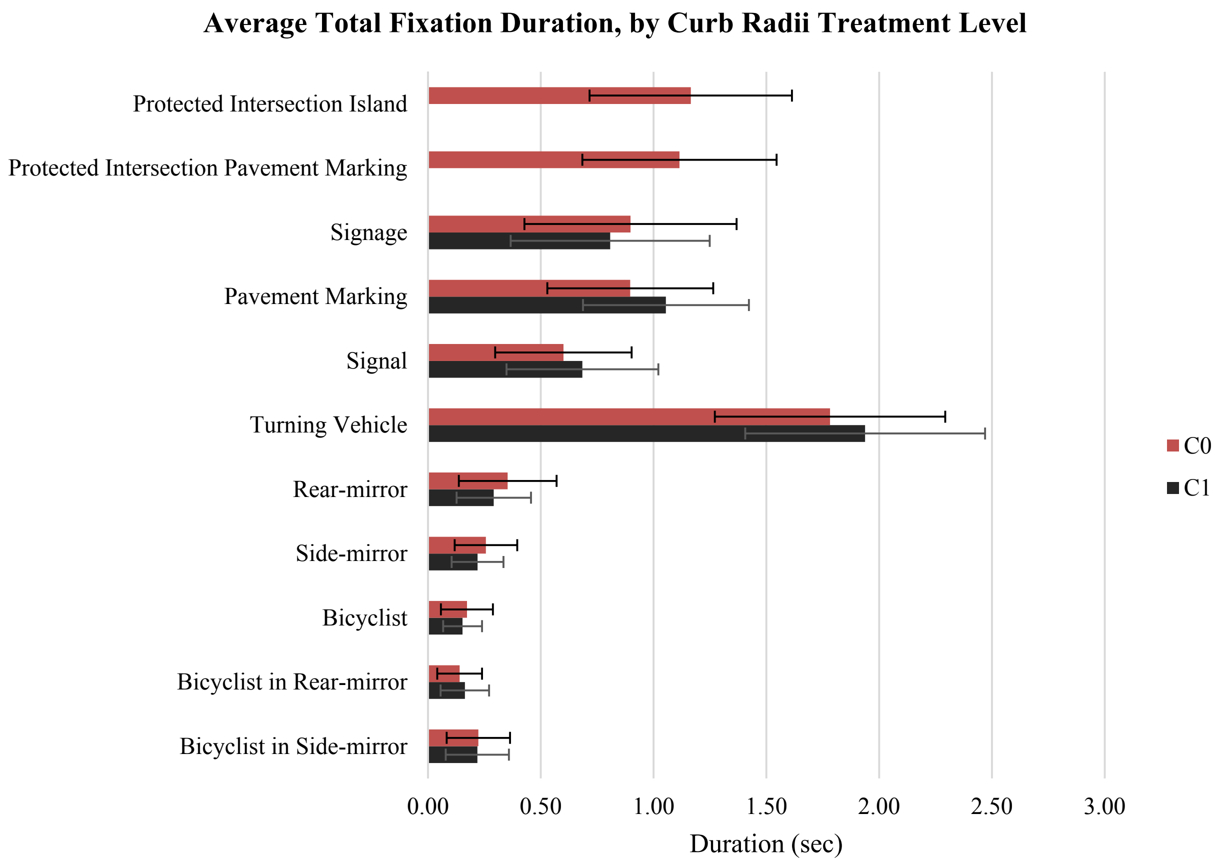


Figure 11.10: Bar plots of ATFD (s) for the curb radii treatment levels (C0= 30ft radii, and C1= 10ft radii)

A two-sample Welch's t-test was performed for all of the AOIs of interest, with respect to the level zero curb radii treatment (C0) and the level one curb radii treatment (C1). These tests compared the ATFDs for C0 and C1 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for C0 and C1. Table 11.8 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants who didn't look at the particular AOIs) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that the only statistically significant difference in ATFDs for C0 and C1 occurred for the "Side Mirror" AOI, with a two-tailed p-value of 0.04. These findings suggest that when the level one curb radii treatment is present, the motorists spent less time fixating on the bicyclist in the side mirror on the approach to the intersection, in comparison to the level zero curb radii treatment (0.44 sec vs 0.52 sec). The ANOVA analysis also showed that fixations on the side mirror had statistically significant differences as measured by ATFDs, with a p-value of 0.04. No other significant differences were found with 95% confidence.

Table 11.8: Statistical analysis of difference in ATFDs by curb radii treatment level

Areas of Interest	Curb Radii Treatment Level		ANOVA	Welch's Two sample two tail *t*-test		
	C0	C1		C0 vs. C1		
	ATFD (sec)		p-value	p-value	Sig	Diff
Side Mirror with Bicyclist	0.58	0.63	0.31	0.31	No	0.05
Rear Mirror with Bicyclist	0.46	0.45	0.57	0.57	No	-0.01
Bicyclist	0.41	0.35	0.45	0.45	No	-0.06
Side Mirror	**0.52**	**0.44**	**0.04***	**0.04***	**Yes**	**-0.08**
Rear Mirror	0.62	0.56	0.93	0.93	No	-0.06
Turning Vehicle	1.93	2.10	0.21	0.21	No	0.17
Signal	0.90	0.99	0.38	0.38	No	0.09
Signage	1.29	1.25	0.76	0.76	No	0.04
Pavement Marking	1.15	1.24	0.50	0.50	No	0.09

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

11.3.1.4 Protected Intersection Treatments

The protected intersection treatment levels are unique, as it is not fully counterbalanced with the rest of the treatments. Therefore, the analysis has been divided into three groups:

1. PI0 (T1) & PI1… (the base intersection treatment with 30ft curb radii, no signage, and no pavement marking) vs. (protected intersection treatment with islands, 30ft curb radii, no signage, and no pavement marking)

2. PI0 (T11) & PI2… (the intersection treatment with 30ft curb radii, signage, no pavement marking) vs. (protected intersection treatment with islands, 30ft curb radii, signage, and green pavement marking)

3. PI1 & PI2… (protected intersection treatment with islands, 30ft curb radii, no signage, and no pavement marking) vs. (protected intersection treatment with islands, 30ft curb radii, signage, and green pavement marking)

PI0 (TI) and PI1

Figure 11.11 shows the ATFDs with 95% CIs on the 11 AOIs for the following protected intersection treatment variable levels: PI0 (T1)= base intersection treatment with 30ft curb radii, no signage, no pavement marking, and PI1= protected intersection treatment with islands, 30ft curb radii, no signage, no pavement marking.

The graphical comparison shows no consistent pattern of change between the ATFDs for the level zero protected intersection treatment (PI0 (T1)) and those of the level one protected intersection treatment (PI1). The ATFDs for the following AOIs decreased for PI1: “Signal,” “Rear Mirror,” “Side Mirror,” and “Bicyclist in Side Mirror.” These findings suggest that when the level one protected intersection treatment is present, drivers spend less time scanning for the bicyclist in the rear and side mirror on the approach to the intersection (0.38 sec vs. 0.47 sec, a 19% decrease, and 0.25 sec vs. 0.33 sec, a 24% decrease, respectively) and significantly less time for the bicyclist in the side mirror in close proximity to the intersection (0.07 sec vs. 0.28 sec, a 75% decrease), as compared to the T1 level zero protected intersection treatment. This significant decrease in the “Bicyclist in Side Mirror” could be due to the fact that with PI1, the driver has an additional AOI (the “Protected Intersection Island,” which averaged to 1.41 sec for the ATFD).

While the ATFDs for these AOIs decreased, the ATFDs for the following AOIs increased for PI1: “Turning Vehicle,” “Bicyclist,” and “Bicyclist in Rear Mirror.” These findings suggest that when the level one protected intersection treatment is present, drivers spent more time scanning for the bicyclist in the rear mirror in close proximity to the intersection, as compared to the T1 level zero protected intersection treatment (0.16 sec vs. 0.15 sec, a 7% increase).

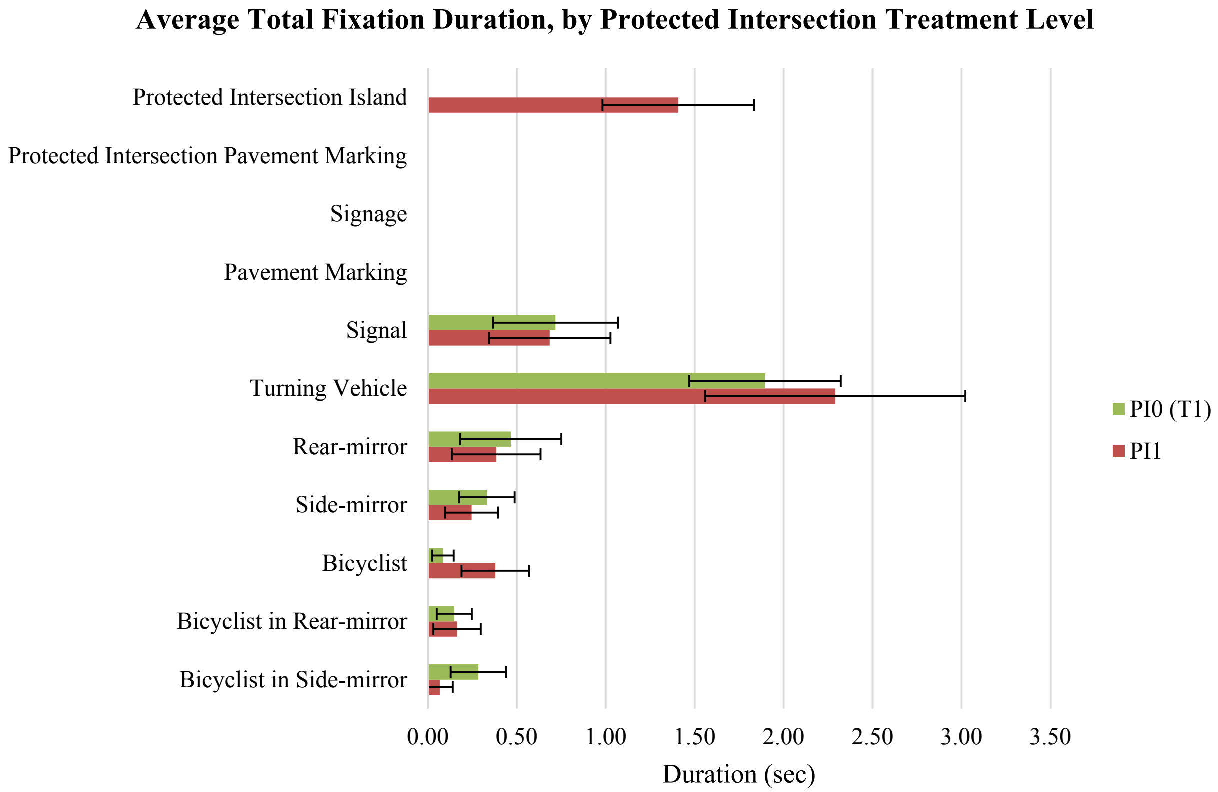


Figure 11.11: Bar plots of ATFD (s) for the group 1 protected intersection treatment levels (PI0 (T1)= base intersection treatment with 30ft curb radii, no signage, no pavement marking, and PI1= protected intersection treatment with islands, 30ft curb radii, no signage, no pavement marking)

A two-sample Welch's t-test was performed for all of the AOIs , with respect to the level zero protected intersection treatment (PI0 (T1)) and the level one protected intersection treatment (PI1). These tests compared the ATFDs for PI0 (T1) and PI1 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PI0 (T1) and PI1. Table 11.9 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that the only statistically significant difference in ATFDs for PI0 (T1) and PI1 occurred for the "Bicyclist" AOI, with a two-tailed p-value of 0.04. These findings suggest that when the level one protected intersection treatment is present, the motorists spent more time fixating on the bicyclist once it is alongside or has passed the vehicle, in comparison to the T1 level zero protected intersection treatment (0.59 sec vs 0.28 sec). The ANOVA analysis also showed that fixations on the side mirror had statistically significant differences as measured by ATFDs, with a p-value of 0.04. No other significant differences were found with 95% confidence.

Table 11.9: Statistical analysis of difference in ATFDs by protected intersection treatment level

Areas of Interest	Protected Intersection Treatment Level		ANOVA	Welch's Two sample two tail *t*-test		
	PI0 (T1)	PI1		PI0 (T1) vs. PI1		
	ATFD (sec)		p-value	p-value	Sig	Diff
Side Mirror with Bicyclist	0.62	0.49	0.68	0.68	No	-0.13
Rear Mirror with Bicyclist	0.43	0.69	0.15	0.15	No	0.26
Bicyclist	0.28	0.59	0.02*	0.02*	Yes	0.31
Side Mirror	0.62	0.62	0.96	0.96	No	0.00
Rear Mirror	0.71	0.69	0.82	0.82	No	-0.02
Turning Vehicle	1.97	2.44	0.56	0.56	No	-0.47
Signal	1.24	1.06	0.64	0.64	No	-0.18

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

PI0 (T11) and PI2

Figure 11.12 shows the ATFDs with 95% CIs on the 11 AOIs for the following protected intersection treatment variable levels: PI0 (T11)= base intersection treatment with 30ft curb radii, signage, no pavement marking, and PI2= protected intersection treatment with islands, 30ft curb radii, signage, green pavement marking.

The graphical comparison shows no consistent pattern of change between the ATFDs for the level zero protected intersection treatment PI0 (T11) and those of the level two protected intersection treatment (PI2). The ATFDs for the following AOIs decreased for PI2: "Signal," "Turning Vehicle," "Side Mirror," "Bicyclist in Side Mirror," and "Bicyclist in Rear Mirror." These findings suggest that when the level two protected intersection treatment is present, drivers spend significantly less time scanning for the bicyclist in the side mirror on the approach to the intersection (0.16 sec vs. 0.33, a 52% decrease) and significantly less time for the bicyclist in the rear and side mirror in close proximity to the intersection (0.09 sec vs. 0.20 sec, a 55% decrease, and 0.15 sec vs 0.20 sec, a 25% decrease, respectively), as compared to the T11 level zero protected intersection treatment. These significant decreases could be due to the fact that with PI2, the driver has two additional AOIs to look at (the "Protected Intersection Island," which averaged to 0.92 sec for the ATFD, and the "Protected Intersection Pavement Marking," which averaged to 1.12 sec for the ATFD).

While the ATFDs for these AOIs decreased, the ATFDs for the following AOIs increased for PI2: “Signage,” “Rear Mirror,” and “Bicyclist.” These findings suggest that when the level two protected intersection treatment is present, drivers spend more time scanning for the bicyclist in the rear mirror on the approach to the intersection, as compared to the T11 level zero protected intersection treatment (0.27 sec vs. 0.19 sec, a 42% increase).

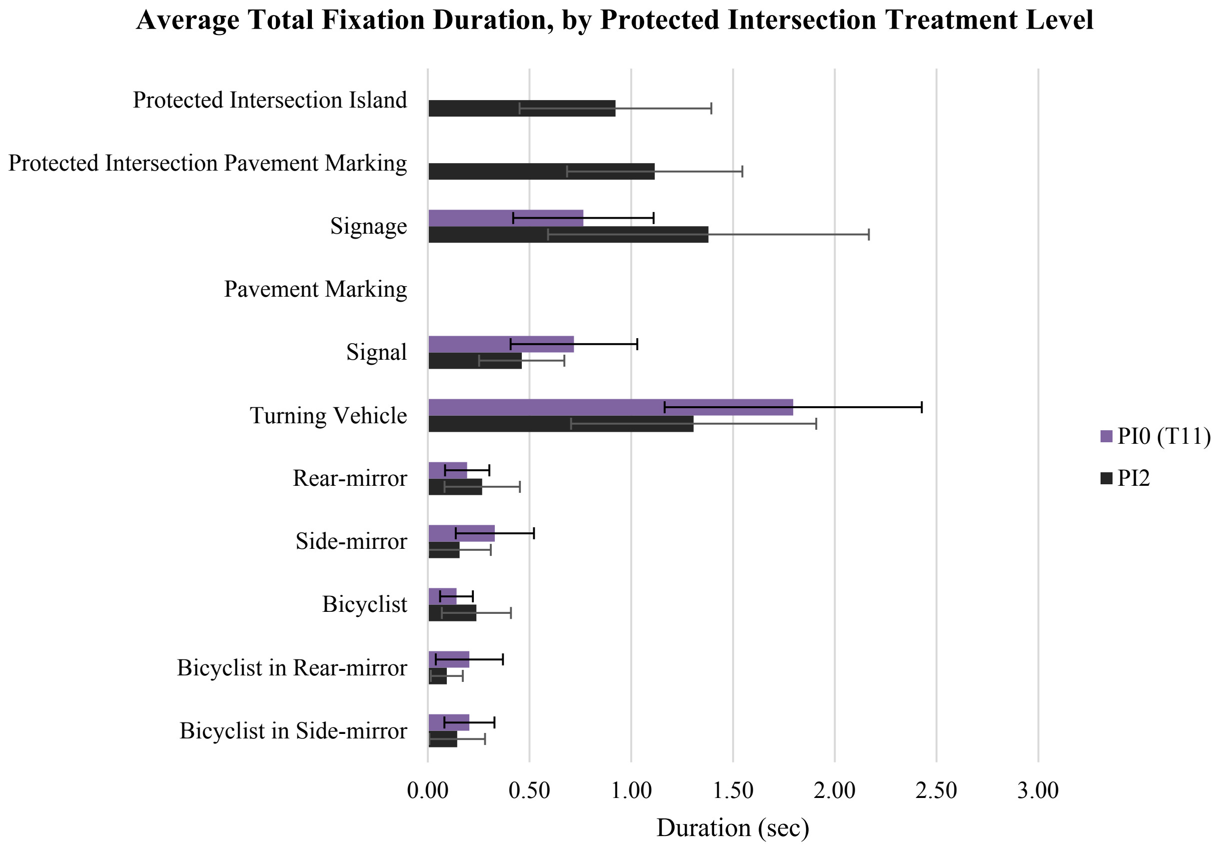


Figure 11.12: Bar plots of ATFD (s) for the group 2 protected intersection treatment levels (PI0 (T11)= base intersection treatment with 30ft curb radii, signage, no pavement marking, and PI2= protected intersection treatment with islands, 30ft curb radii, signage, green pavement marking)

A two-sample Welch’s t-test was performed for all of the AOIs, with respect to the level zero protected intersection treatment (PI0 (T11) and the level two protected intersection treatment (PI2). These tests compared the ATFDs for PI0 (T11) and PI2 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PI0 (T11) and PI2. Table 11.10 presents the results of these two tests.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn’t look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test and the ANOVA analysis did not result in any statistically significant differences between PI0 (T11) and PI2, as measured by ATFDs, with 95% confidence.

Table 11.10: Statistical analysis of difference in ATFDs by protected intersection treatment level

Areas of Interest	Protected Intersection Treatment Level		ANOVA	Welch's Two-sample two-tail *t*-test		
	PI0 (T11)	PI2		PI0 (T11) vs. PI2		
	ATFD (sec)		p-value	p-value	Sig	Diff
Side Mirror with Bicyclist	0.50	0.57	0.48	0.48	No	0.07
Rear Mirror with Bicyclist	0.40	0.57	0.67	0.67	No	0.17
Bicyclist	0.51	0.36	0.38	0.38	No	-0.15
Side Mirror	0.45	0.71	0.19	0.19	No	0.26
Rear Mirror	0.46	0.34	0.27	0.27	No	-0.12
Turning Vehicle	1.56	2.01	0.17	0.17	No	0.45
Signal	0.55	1.01	0.13	0.13	No	0.46
Signage	1.90	1.07	0.19	0.19	No	-0.83

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

PI1 and PI2

Figure 11.13 shows the ATFDs with 95% CIs on the 11 AOIs for the following protected intersection treatment variable levels: PI1= protected intersection treatment with islands, 30ft curb radii, no signage, no pavement marking and PI2= protected intersection treatment with islands, 30ft curb radii, signage, green pavement marking.

The graphical comparison shows that while most of the ATFDs decreased for PI2, there was an increase in the ATFDs for the "Bicyclist in Side Mirror" AOI. This finding suggests that when the level two protected intersection treatment is present, drivers spent more time scanning for the bicyclist in the side mirror in close proximity to the intersection, in comparison to the level one protected intersection treatment (0.15 sec vs 0.07 sec).

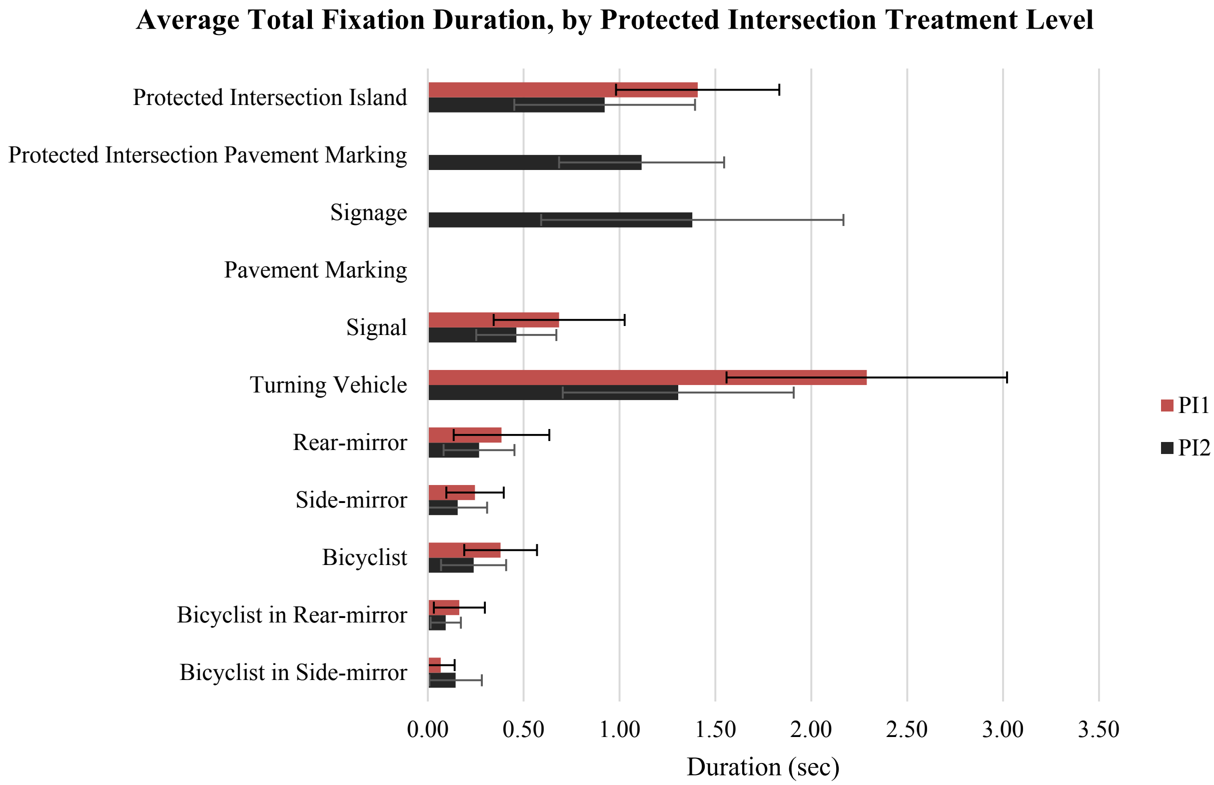


Figure 11.13: Bar plots of ATFD (s) for the group 3 protected intersection treatment levels (PI1= protected intersection treatment with islands, 30ft curb radii, no signage, no pavement marking and PI2= protected intersection treatment with islands, 30ft curb radii, signage, green pavement marking)

A two-sample Welch's t-test was performed for all of the AOIs, with respect to the level one protected intersection treatment (PI1) and the level two protected intersection treatment (PI2). These tests compared the ATFDs for PI1 and PI2 to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the ATFDs for PI1 and PI2. Table 11.11 presents the results of these two tests, with statistically significant p-values shown in bold.

It is important to note that the ATFD distributions for the AOIs were significantly skewed to the right, and needed to be log-transformed to closer represent a more normal distribution for the statistical tests. In order to proceed with the log transformation, the zero values (for those participants that didn't look at the particular AOI) were removed from the dataset for these tests. Therefore, the test results represent the sub-group of drivers who did look at the particular AOIs.

The two-sample Welch's t-test revealed that a statistically significant difference in ATFDs for PI1 and PI2 occurred for the "Turning Vehicle" and "Signal" AOI, with a two-tailed p-values of 0.04 and 0.04, respectively. These findings suggest that when the level two protected intersection treatment is present, the motorists spent less time fixating on the turning vehicle and the traffic signal (1.56 sec vs 2.44 sec and 0.55 sec vs 1.06 sec), in comparison to the level one protected intersection treatment. This change may influence the ATFDs for the bike-related AOIs in that a greater portion of their visual attention can now be allocated to the ATFDs for those bike-related AOIs. The ANOVA analysis also showed that fixations on the oncoming turning vehicle and the traffic signal had statistically significant differences, as measured by ATFDs, with p-values of 0.04 and 0.04, respectively. No other significant differences were found with 95% confidence.

Table 11.11: Statistical analysis of difference in ATFDs by protected intersection treatment level

Areas of Interest	Protected Intersection Treatment Levels		ANOVA	Welch's Two sample two tail *t*-test		
	PI1	PI2		PI1 vs. PI2		
	ATFD (sec)		p-value	p-value	Sig	Diff
Side Mirror with Bicyclist	0.49	0.50	0.90	0.90	No	0.01
Rear Mirror with Bicyclist	0.69	0.40	0.07	0.07	No	-0.29
Bicyclist	0.59	0.51	0.55	0.55	No	-0.08
Side Mirror	0.62	0.45	0.25	0.25	No	-0.17
Rear Mirror	0.69	0.46	0.65	0.65	No	-0.23
Turning Vehicle	**2.44**	**1.56**	**0.04***	**0.04***	**Yes**	**-0.88**
Signal	**1.06**	**0.55**	**0.04***	**0.04***	**Yes**	**0.51**
Protected Intersection Island	1.62	1.07	0.13	0.13	No	0.55

Note: For these statistical tests, the zeros have been removed in order to log-transform the data

11.3.2 Effect of Engineering Treatments on Motorists Fisating on Bicyclist

In addition to the assessment of the ATFDs on the bicyclist, with respect to different treatments and their respective levels, another research interest ($H_{0\ (VSP2)}$) was to investigate the percentage of motorists who fixated on the bicyclist before turning right at an intersection. As stated previously, the participants were considered to have looked for the bicyclist if at least one of the following variables was greater than zero ("Side Mirror," "Rear Mirror," "Bicyclist in Side Mirror," or "Bicyclist in Rear Mirror"). Table 11.12 presents the percentage of the all right-turn maneuvers where the motorist fixated on the bicyclist-related AOIs before turning right. Of the 596 right-turn maneuvers, 470 maneuvers (79%) involved participants looking for the bicyclist and 126 maneuvers (21%) did not involve participants looking for the bike.

Table 11.12: Frequency of motorist fixation on bicyclist before turning right

Frequency of fixation	Total
Total (n)	596
Fixated	470
% Fixated	79%

Individual motorist fixations behavior was examined for the four treatment levels: signage (S), pavement marking (PM), curb radii (C), and protected intersections (PI). A Chi-square test revealed no statistically significant difference between the frequencies of motorist fixations on the bicyclist of the different treatment levels. Table 11.13 presents the p-value results of these chi-square tests.

Table 11.13: Chi-square test for independence results for treatment levels and motorist fixation on bicyclist before turning right

Treatment Variable	P value	Significant
S	0.3233	No
PM	0.1684	No
C	0.5181	No
PI	0.7912	No

In order to gain a better understanding of the impacts of the different treatment levels on the motorist fixations on the bicyclist, within each treatment type, this analysis was further broken down by four treatment types.

11.3.2.1 Signage

Table 11.14 presents the rates of the right-turn maneuvers where the motorist fixated on the bicyclist-related AOIs before turning right, separated by the signage treatment levels: S0 and S1. Of the two levels, S1 showed a 4% higher rate of motorist fixations on the bicyclist, with 81% of the right-turn maneuvers involving participants looking for the bicyclist.

Table 11.14: Frequency of motorist fixation on bicyclist before turning right, S

Frequency of fixation	Signage Treatment Level	
	S0	S1
Total (n)	296	300
Fixated	228	242
% Fixated	77%	81%

11.3.2.2 Pavement Marking

Table 11.15 presents the rates of the right-turn maneuvers where the motorist fixated on the bicyclist-related AOIs before turning right, separated by the pavement marking treatment variables levels: PM0, PM1, PM2, PM3, and PM4. All treatments, PM1, PM2, PM3, and PM4, showed higher rates of motorist fixations on the bicyclist, in comparison to PM0 (1%, 10%, 9%, and 10%, respectively). Of these five levels, PM2 and PM4 showed the higher rate of motorist fixations on the bicyclist, with 83% of the right-turn maneuvers involving participants looking for the bicyclist (10% increase, compared to PM0).

Table 11.15: Frequency of motorist fixation on bicyclist before turning right, PM

Frequency of fixation	Pavement Marking Treatment Level				
	PM0	PM1	PM2	PM3	PM4
Total (n)	109	78	90	89	91
Fixated	80	106	109	108	110
% Fixated	73%	74%	83%	82%	83%

11.3.2.3 Curb Radii

Table 11.16 presents the rates of the right-turn maneuvers where the motorist fixated on the bicyclist-related AOIs before turning right, separated by the two curb radii treatment levels: C0 and C1. Of the two levels, C0 showed the higher rate of motorist fixations on the bicyclist, with 80% of the right-turn maneuvers involving participants looking for the bicyclist.

Table 11.16: Frequency of motorist fixation on bicyclist before turning right, C

Frequency of fixation	Curb Radii Treatment Level	
	C0	C1
Total (n)	325	271
Fixated	260	210
% Fixated	80%	77%

11.3.2.4 Protected Intersection

Table 11.17 presents the rates of the right-turn maneuvers where the motorist fixated on the bicyclist-related AOIs before turning right, separated by the protected intersection treatment levels used previously in the ATFD analysis: PI0 (T1), PI0 (T11), PI1, and PI2.

As a reminder, PI0 (T1) is the base intersection treatment with 30ft curb radii, no signage, and no pavement marking and PI0 (T11) is the intersection treatment with 30ft curb radii, signage, no pavement marking.

Between PI0 (T1) and PI1, PI0 (T1) showed the higher rate of motorist fixations on the bicyclist, with 77% of the right-turn maneuvers involving participants looking for the bicyclist. Between PI0 (T11) and PI2, PI2 showed the higher rate of motorist fixations on the bicyclist, with 81% of the right-turn maneuvers involving participants looking for the bicyclist. Between PI1 and PI2, PI2 showed the higher rate of motorist fixations on the bicyclist, with 81% of the right-turn maneuvers involving participants looking for the bicyclist.

Table 11.17: Frequency of motorist fixation on bicyclist before turning right, PI

Frequency of fixation	Protected Intersection Treatment Level			
	PI0 (T1)	PI0 (T11)	PI1	PI2
Total (n)	26	28	27	27
Fixated	20	21	20	22
% Fixated	77%	75%	74%	81%

11.4 SUMMARY

This study investigated motorists' visual attention to assess if motorists actively search for bicyclists before turning right at a signalized intersection - an important condition to avoid a right-hook crash. Of the 596 right-turn maneuvers made by the 28 participants, 79% of those maneuvers involved the motorist actively searching for the bicyclist in the rear or side mirror. This chapter examined the effect of various treatments, (specifically, signage, pavement markings, curb radii, and protected intersections), on the visual attention of motorists, particularly how that effect may contribute to right-hook crashes.

A Chi-square test revealed no statistically significant difference between the frequencies of motorist fixations on the bicyclist-related AOIs for the different treatment levels. However, the findings provide an indication that some of the treatments may be effective methods in positively influencing driver behavior, with respect to the visual attention. The findings are summarized as follows:

Concerning the signage treatments, the findings indicate that the S1 signage treatment appears to be an effective method of positively influencing driver behavior, with respect to visual attention.

There is a generally positive pattern of change in visual attention between the level one and level zero signage treatments. The level one signage treatment showed a 4% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero signage treatment. It specifically increased the amount of time spent scanning the side mirror for the bicyclist by 9% and the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 10%, in comparison to the level zero signage treatment.

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 level one signage treatment is present. The driver is already looking in that direction, so it may feel natural to simply continue moving the scan path to the right, towards the passenger side mirror. Either way, this increased amount of time could reduce the frequency of right-hook crashes by increasing the likelihood that a driver identifies a bicyclist.

Concerning the pavement markings treatments, the findings indicate that the PM2 pavement marking treatment appears to be an effective method of positively influencing the driver *behavior, with respect to visual attention. They also indicate that PM4 does not appear to be an effective method. It is unclear whether PM1 or PM3 appear to be effective methods.*

There is no consistent pattern of change in visual attention between the level one and the level zero pavement marking treatments. The level one pavement marking treatment showed a 1% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment. It specifically increased the amount of time spent scanning the rear mirror by 13% and the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 13%, in comparison to the level zero pavement marking treatment. However, the presence of the level one pavement marking treatment also decreased the amount of time spent scanning the side mirror by 11% and the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 8%, in comparison to the level zero pavement marking treatment.

There is a generally positive pattern of change in visual attention between the level two and the level zero pavement marking treatments. The presence of the level two pavement marking treatment showed a 10% increase in motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment (it is tied with the level four pavement marking treatment for the highest rate for all five pavement marking treatment levels). It also specifically increased the amount of time motorists' spent scanning the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 13%, in comparison to the level zero pavement marking treatment. However, the presence of the level two pavement marking treatment also decreased the amount of time motorists' spent scanning the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 6%, in comparison to the level zero pavement marking treatment.

There is no consistent pattern of change in visual attention between the level three and the level zero pavement marking treatments. The presence of the level three pavement marking treatment showed a 9% increase in motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment. It specifically increased the amount of time motorists' spent scanning the rear mirror by 10%, in comparison to the level zero pavement marking treatment. However, the presence of the level three pavement marking treatment also decreased the amount of time motorists' spent scanning the side mirror by 12% and the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 6%, in comparison to the level zero pavement marking treatment.

There is a generally negative pattern of change in visual attention between the level four and the level zero pavement marking treatments. The presence of the level four pavement marking treatment showed a 10% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment (it is tied with the level two pavement marking treatment for the highest rate for all five pavement marking treatment levels). However, the level four pavement marking treatment decreased the amount of time spent scanning the rearview and side mirrors in close proximity to the intersection (when the bicyclist is visible) by 12% and 22%, respectively, and the amount of time spent scanning the side mirror on the approach by 4%, in comparison to the level zero pavement marking treatment. The decrease in the amount of time spent scanning the side mirror in close proximity to the intersection was found to be statistically significant (p-value = 0.03).

Concerning the curb radii treatments, the findings are unclear whether the C1 curb radii treatment appears to be an effective method of positively influencing driver behavior, with respect to visual attention.

There is no consistent pattern of change in visual attention between the level one and level zero curb radii treatments. The presence of the smaller, level one curb radii treatment showed a 3% lower rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero curb radii treatment. The level one curb radii treatment decreased the amount of time spent scanning the side mirror by 15% and the rear mirror by 17%, in comparison to the level zero curb radii treatment. The decrease in the amount of time spent scanning the side mirror was found to be statistically significant (p-value = 0.04). However, the presence of the smaller, level one curb radii treatment increased the amount of time spent scanning the rearview mirror for the bicyclist in close proximity to the intersection (when the bicyclist is visible) by 14%, in comparison to the level zero curb radii treatment.

Concerning the protected intersection treatments, the findings indicate that the PI1 protected intersection treatment does not appear to be an effective method of positively influencing driver behavior, with respect to visual attention. It is unclear whether PI2 appears to be an effective method.

There is a generally negative pattern of change in visual attention between the level one and level zero protected intersection treatments. The presence of the level one protected intersection treatment showed a 3% lower rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero protected intersection treatment. It decreased the amount of time spend scanning the rear mirror by 19%, the side mirror by 24%, and the side mirror in close proximity to the intersection (when the bicyclist is visible in the side mirror) by 75%, in comparison to the level zero protected intersection treatment. However, it also increased the amount of time spent scanning the rear mirror for the bicyclist in close proximity to the intersection (when the bicyclist is visible in the rear mirror) by 7%, in comparison to the level zero protected intersection treatment.

There is no consistent pattern of change in visual attention between the level two and level zero protected intersection treatments. The presence of the level two protected intersection treatment showed a 6% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero protected intersection treatment. It specifically increased the amount of time spent scanning the rear mirror for the bicyclist by 42%, in comparison to the level zero protected intersection treatment. However, it decreased the amount of time spent scanning the side mirror by 52%, and the rear and side mirror in close proximity to the intersection (when the bicyclist is visible in the mirror) by 55% and 25%, respectively, in comparison to the level zero protected intersection treatment.

12.0 RESULTS: EXPERIMENT 2 CRASH AVOIDANCE

This chapter explores the performance of a right-turning motorist through the global performance measure of crash avoidance. Motorists were exposed to crash-likely scenarios in the driving simulator (i.e., oncoming left-turning vehicle and a bicyclist in the blind spot) with varying combinations of engineering treatment levels in order to analyze the motorist behavior to measure the effectiveness of engineering treatments in preventing the occurrence of right-hook crashes.

12.1 DESCRIPTION OF EXPERIMENT

The objective of this experiment was to assess the effectiveness of engineering treatments by analyzing the right-turning motorists' behavior in a crash-likely scenario. Specifically, if the treatments affect how well motorists are able to detect the potential hazard (i.e., the bicyclist in the adjacent bicycle lane) and avoid a crash with the bicyclist while performing a right turn during the latter portion of the green phase at a signalized intersection.

The following two hypotheses were formulated for each of the four treatment types:

- $H_{0\,(CA1)}$: The engineering treatments have no effect on the right-turning motorists' crash outcomes for near-collisions or collisions.

- $H_{0\,(CA2)}$: The engineering treatments have no effect on the right-turning motorists' time to collision values at the time of near-collisions or collisions.

Crash avoidance is measured by considering the 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. As mentioned before, 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).* The participant could avoid colliding with the bicyclist by detecting it in the rear or side mirror. The bicyclist was situated as such that the motorist would likely hit the bicyclist approaching from the vehicle's blind spot unless the bicyclist was detected in the mirrors.

Motorists' crash avoidance behavior was observed during every right-turn maneuver (n=22), as described in Chapter 4. Motorists driving in the simulated environment were observed continuously from the simulator's operator station and recorded with the head-mounted mobile eye tracker worn by the participant. The eye-tracker video records were further analyzed and the crashes and near-collisions were noted. The recorded crash data was further validated by checking the locations of the subject vehicle and bicycle centroid, recorded as dynamic variable data in the driving simulator.

12.2 DATA ANALYSIS

The motorist crash avoidance behavior was assessed by performing descriptive statistics and statistical analysis in Microsoft Excel and R statistical software.

12.2.1 Contributing Crash Factors

In this experiment, 28 participants each completed 22 right-turn maneuvers, in total 616 right turns were made. Seventy-five total incidents were observed during 616 right turns. These 75 incidents included 47 near-collisions and 28 collisions, and were made across 21 treatments by 20 participants, 13 (65%) of whom crashed more than once. Both environmental factors and motorist factors serve as crash factors; however, only the environmental factor will be assessed for Experiment 2.

Figure 12.1 displays the distribution of these near-collision and collision incidents across the 22 treatments (see Table 12.1 for the distribution of S, PM, C, and PI treatment levels across the 22 treatments). The only treatment to not experience any incidents is Treatment 7, (which consisted of S0= no signage, PM1=a single, dotted white bike line with stencil, C1=a 10ft curb radii, and PI0= no protected intersection). The two treatments with the next lowest amount of incidents is Treatment 16 (which consisted of S1= signage, PM0=no pavement marking, C1=a 10ft curb radii, and PI0= no protected intersection) and Treatment 19 (which consisted of S1= signage, PM3= a skipped green bike lane with white outline, C1=a 10ft curb radii, and PI0= no protected intersection). The highest was Treatment 2 (which consisted of S0= no signage, PM1=a single, dotted white bike line with stencil, C0=a 30ft curb radii, and PI0= no protected intersection).

Figure 12.2 displays the distribution of these near-collision and collision incidents across the 20 participants. Eight of the 28 participants (29%) did not experience any incidents. The highest number of incidents for any one participant was 17 incidents; the next highest was 8 incidents.

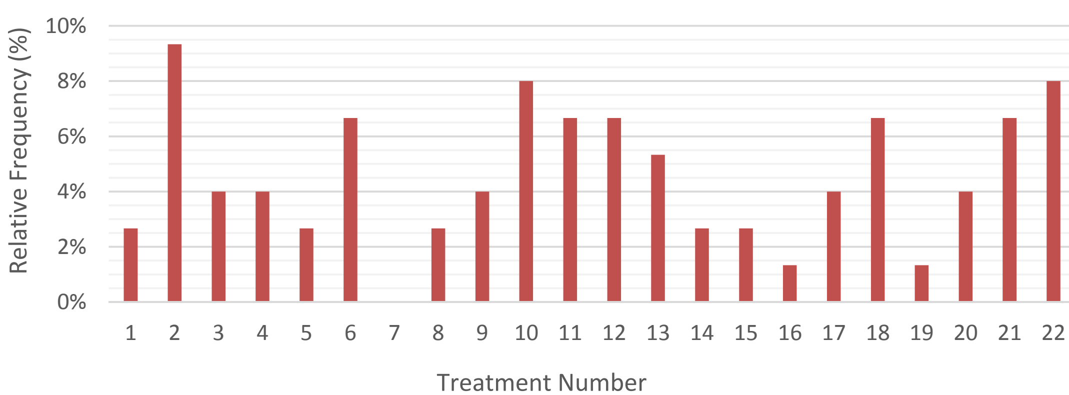


Figure 12.1: Relative frequency of near-collisions and collisions by treatments

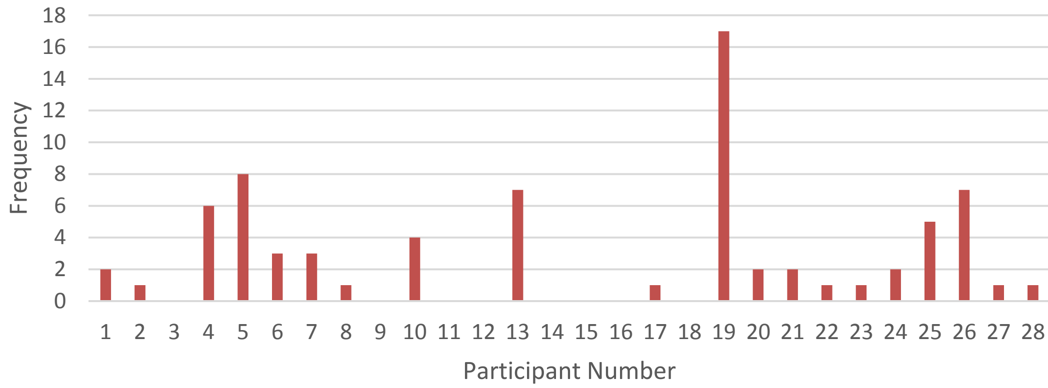


Figure 12.2: Frequency of near-collisions and collisions by participant

12.2.1.1 Driving Environmental Factors

The driving environmental factors during observed incidents included the treatment levels spread across the 22 treatment combinations (see Table 12.1 for the distribution of S, PM, C, and PI treatment levels across the 22 treatment combinations). Figure 12.3presents the distribution of the relative frequency of the near-collisions and collisions across the treatments. These 75 incidents included 47 near-collisions and 28 collisions. The treatments with the three highest relative frequency of collisions are Treatment 11 and Treatment 22 (tied at 14 %), followed by Treatment 10 (11%). The treatments with the five lowest relative frequency of collisions are Treatment 1, Treatment 3, Treatment 5, Treatment 6, and Treatment 16 (tied at 4 %).

Table 12.1 describes the exact independent variables that were present in the driving scenario where an incident was observed. The treatments with the three highest number of incidents are Treatment 2 (7 incidents), followed by Treatment 11 and Treatment 22 (tied at 6 incidents). The treatments with the three lowest number of incidents are Treatment 7(0 incidents), followed by Treatment 16 and Treatment 19 (tied at 1 incident).

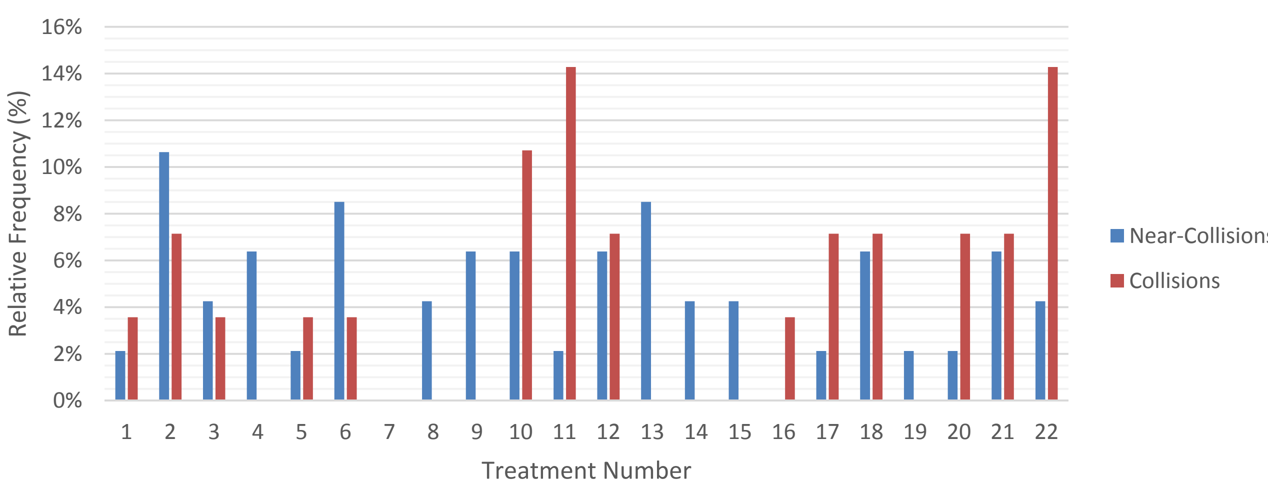


Figure 12.3: Relative frequency of near-collisions and collisions by treatment

A Chi-square test was performed for the treatments to test for any statistically significant differences between levels. Table 12.1 displays the resulting p-values, with statistically significant p-values shown in bold. These tests revealed a statistically significant difference between the PM0 pavement marking treatment level and the PM3 pavement marking treatment level (p-value = 0.01) with respect to the incident outcomes. (Table 12.2) This finding suggests that the presence of the level three pavement marking treatment will be associated with a lower number of collisions, compared the level zero pavement marking treatment. No other statistically significant differences were found with 95% confidence.

Table 12.1: Independent variable levels during observed incidents

T #	S	PM	C	PI	Number of Incidents		
					Near-collision	Collision	Total
1	No Signage	No pavement marking	30ft curb radii	N/A	1	1	2
2	No Signage	Single white dotted line, bicycle stencil	30ft curb radii	N/A	5	2	7
3	No Signage	Double white dotted line, bicycle stencil	30ft curb radii	N/A	2	1	3
4	No Signage	Skipped green	30ft curb radii	N/A	3	0	3
5	No Signage	Solid green	30ft curb radii	N/A	1	1	2
6	No Signage	No pavement marking	30ft curb radii	N/A	4	1	5
7	No Signage	Single white dotted line, bicycle stencil	30ft curb radii	N/A	0	0	0
8	No Signage	Double white dotted line, bicycle stencil	30ft curb radii	N/A	2	0	2
9	No Signage	Skipped green	30ft curb radii	N/A	3	0	3
10	No Signage	Solid green	30ft curb radii	N/A	3	3	6
11	Signage	No pavement marking	10ft curb radii	N/A	1	4	5
12	Signage	Single white dotted line, bicycle stencil	10ft curb radii	N/A	3	2	5
13	Signage	Double white dotted line, bicycle stencil	10ft curb radii	N/A	4	0	4
14	Signage	Skipped green	10ft curb radii	N/A	2	0	2
15	Signage	Solid green	10ft curb radii	N/A	2	0	2
16	Signage	No pavement marking	10ft curb radii	N/A	0	1	1
17	Signage	Single white dotted, bicycle stencil	10ft curb radii	N/A	1	2	3
18	Signage	Double white dotted, bicycle stencil	10ft curb radii	N/A	3	2	5
19	Signage	Skipped green	10ft curb radii	N/A	1	0	1
20	Signage	Solid green	10ft curb radii	N/A	1	2	3
21	No Signage	N/A	30ft curb radii	Protected intersection, with islands	3	2	5
22	Signage	N/A	30ft curb radii	Protected intersection, with islands and green pavement marking	2	4	6
				Total:	**47**	**28**	**75**

Table 12.2: Statistical analysis test for crash outcomes of near-collisions and collisions

Treatment Variables Compared		p-value	Significant
S0	S1	0.20	No
PM0	PM1	0.59	No
PM0	PM2	0.10	No
PM0	**PM3**	**0.01***	**Yes**
PM0	PM4	0.90	No
C0	C1	1.00	No
PI0 (T1)	PI1	1.00	No
PI0 (T11)	PI2	1.00	No
PI1	PI2	0.78	No

*PM0 has 11 near-collisions and 13 collisions, whereas PM3 only has 9 near-collisions

12.2.2 **Analysis of Conflicts**

Traffic conflicts between a right-turning motorist and through-moving bicyclist were calculated where a collision was imminent if the trajectories remained unchanged. Similar to Experiment 1, the traffic conflicts were analyzed with respect to the risk of collisions through the use of the same TTC calculations. Figure 12.4 displays the distribution of TTC values for all observed incidents, showing that 57% of the traffic conflicts had TTCs equal to or less than 1.5 seconds

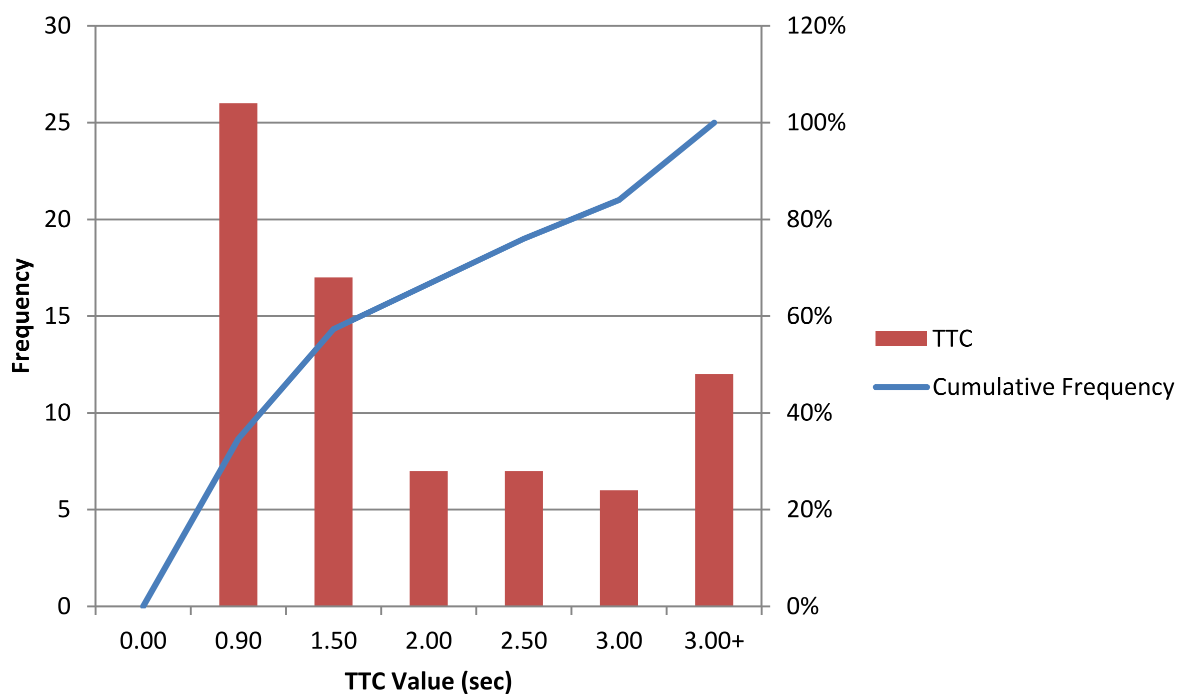


Figure 12.4: TTC frequency and cumulative frequency distributions for all incidents

12.2.2.1 Data Analysis and Result

Using the same equations from Chapter 9, the TTC was calculated for the right-turn maneuvers with incidents. Figure 12.5-7 displays the number of traffic conflicts, and corresponding TTC values, for treatment levels. There were a total 75 conflict events among the 616 right turns. However, according to the 1.5-second TTC threshold value and the ROC score , only 26 incidents could be considered having high (0-0.9 seconds) (n=8) or moderate risk (1.0-1.5 seconds) (n=18) TTC values *(Brown 1994; Gettman et al 2008; Sayed et al. 1999).* The frequency and cumulative frequency distribution were plotted for the various treatment levels. In this case, cumulative frequency represents the percentage of incidents with TTC values that fall below either 0.9 seconds or 1.5 seconds, (as specified), out of the total number of incidents that occurred for the specific treatment level. All of the treatments also had incidents with TTC values greater than 1.5 seconds, but they are not shown here within this analysis.

Figure 12.5 demonstrates the frequency distribution and cumulative frequency distribution of TTC values for the signage treatment levels: S0 and S1. The S1 treatment level has a lower cumulative frequency of high-risk TTC values, (equal to or less than 0.9 seconds), in comparison to S0 (29% vs. 36%, a 7% decrease). However, S1 showed a higher cumulative frequency of moderate- and high-risk TTC values, (equal to or less than 1.5 seconds), in comparison to S0 (59% vs. 56%, a 3% increase).

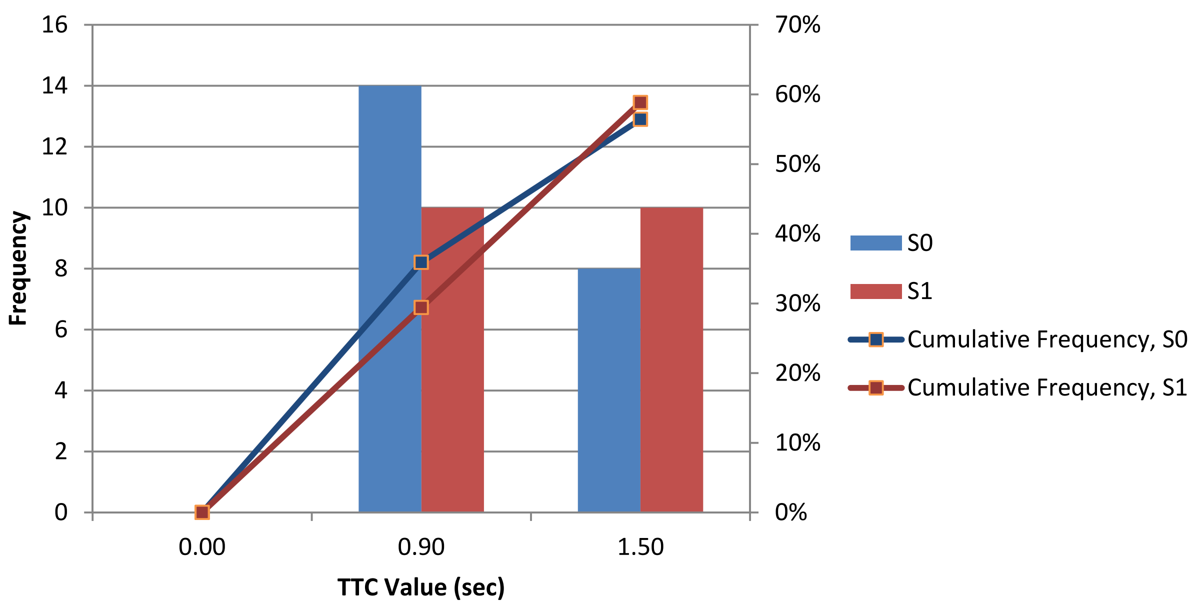


Figure 12.5: TTC frequency and cumulative frequency distributions, by signage treatment levels

Figure 12.6 demonstrates the frequency distribution and cumulative frequency distribution of TTC values for the pavement marking treatment levels: PM0, PM1, PM2, PM3, and PM4.

The cumulative frequency of high-risk TTC values (equal to or less than 0.9 seconds) decreases with PM1, PM3, and PM4, in comparison to PM0 (20%, 20%, and 25%, respectively, vs. 38%). However, PM2 showed an increase in the cumulative frequency of high-risk TTC values, in comparison to PM0 (50% vs. 38%). The treatment levels with the lowest cumulative frequency of high-risk TTCs are PM1 and PM3, tied at 20%. The treatment level with the highest is PM2, at 50%.

The cumulative frequency of moderate- and high-risk TTC values (equal to or less than 1.5 seconds) decreases with the PM1, PM2, PM3, and PM4, in comparison to PM0 (47%, 58%, 60%, and 50%, respectively, vs. 62%). In order of the smallest decrease to the largest decrease: PM3, PM2, PM4, and PM1, (60%, 58%, 50%, and 47%, respectively). It can be seen that PM1 shows the largest decrease in the cumulative frequency of moderate- and high-risk TTC values, in comparison to PM0 (47% vs 62%, a 15% decrease).

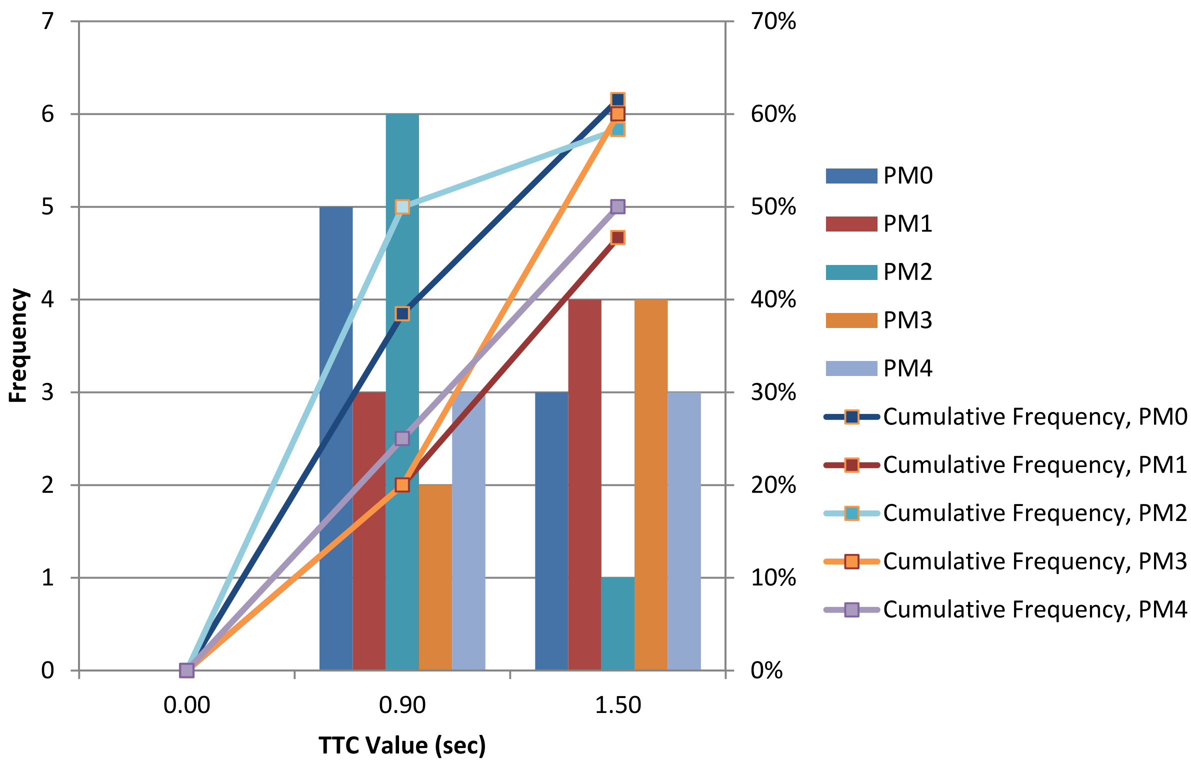


Figure 12.6: TTC frequency and cumulative frequency distributions, by pavement marking treatment levels

Figure 12.7 demonstrates the frequency distribution and cumulative frequency distribution of TTC values for the curb radii treatment levels: C0 and C1. The C1 treatment level has the same cumulative frequency of high-risk TTC values (equal to or less than 0.9 seconds) in comparison to C0 (33%). Additionally, C1 showed a lower cumulative frequency of moderate- and high-risk TTC values (equal to or less than 1.5 seconds) in comparison to C0 (54% vs. 63%, a 7% decrease).

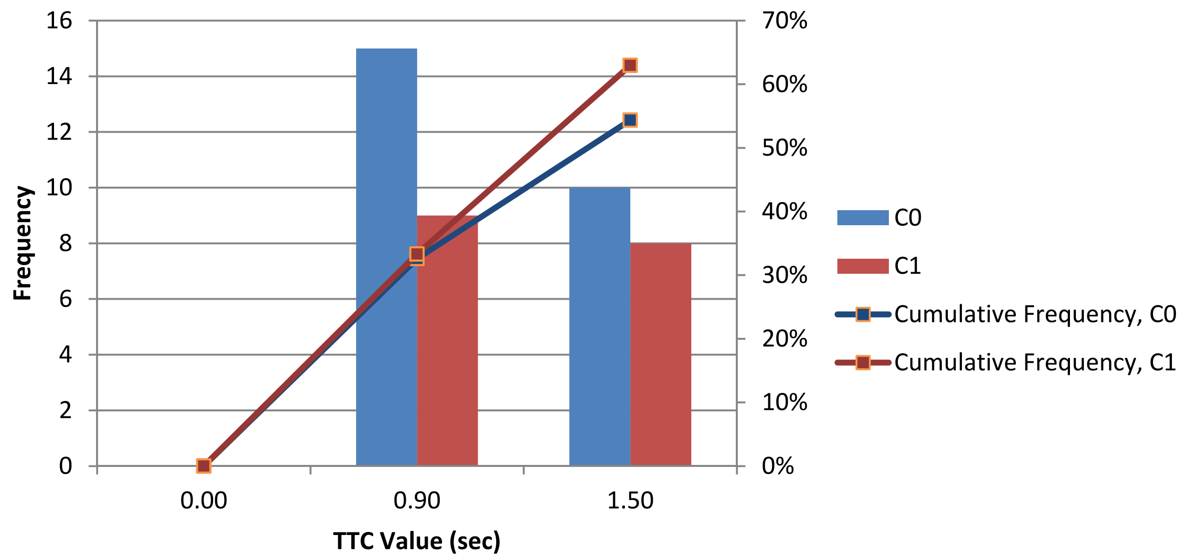


Figure 12.7: TTC frequency and cumulative frequency distributions, by curb radii treatment levels

Figure 12.8 demonstrates the frequency distribution and cumulative frequency distribution for the protected intersection treatment levels: PI0 (T1), PI0 (T11), PI1, and PI2. The cumulative frequency of high-risk TTC values (equal to or less than 0.9 seconds) decreased with both PI1 and PI2, in comparison to PI0 (T1) and PI0 (T11) (31% vs. 50% and 45% vs 60%, respectively). However, the cumulative frequency of moderate- and high-risk TTC values (equal to or less than 1.5 seconds) increased with both PI1 and PI2, in comparison to PI0 (T1) and PI0 (T11) (55% vs. 50% and 73% vs 60%, respectively).

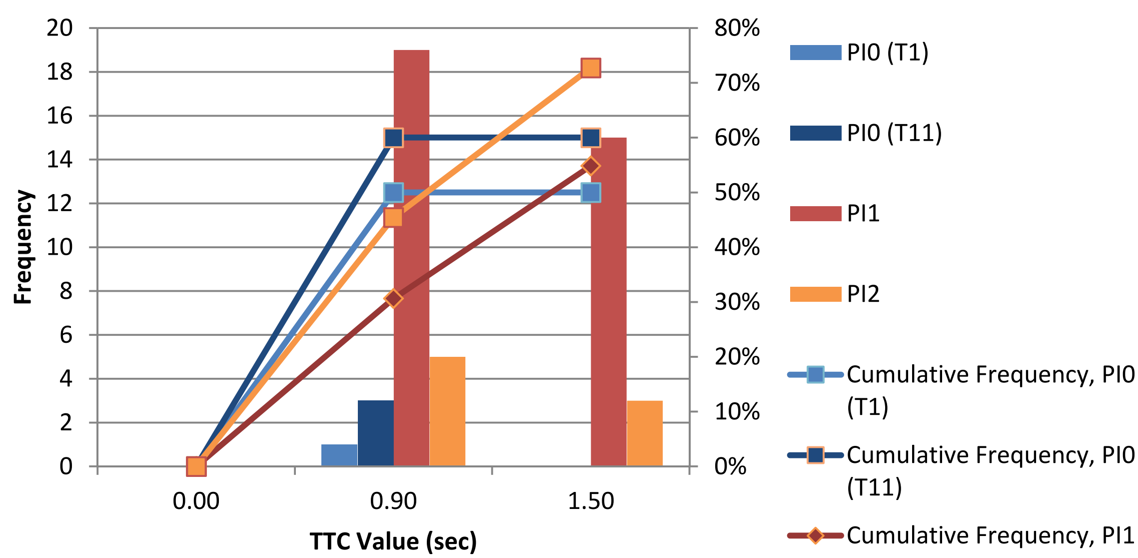


Figure 12.8: TTC frequency and cumulative frequency distributions, by protected intersection treatment level

12.2.3 **Statistical Analysis**

A Chi-square test was performed for the treatments to test for any statistically significant differences between the ROC scores of the various treatment levels. The ROC scores are directly calculated from the TTC values; therefore, this can serve as a test for significant differences in the TTC value bins within the frequency and cumulative frequency distributions, shown within Figures 12.5, 12.6, 12.7, and 12.8. Table 12.3: Statistical analysis test for roc scores of near-collisions and collisions displays the resulting p-values. No statistically significant differences were found with 95% confidence.

Table 12.3: Statistical analysis test for roc scores of near-collisions and collisions

Treatment Variables 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

12.3 SUMMARY

The performance of a right-turning motorist was assessed through the global performance measure of crash avoidance. The crash avoidance behavior observed in this experiment indicated motorists' ability to detect a bicyclist in a timely manner, and make appropriate decisions to avoid a crash with that bicyclist while turning right at a signalized intersection.

Among 28 participants completing a total of 616 right turns, 23 participants could not avoid a crash with a bicyclist in 26 right-hook crash scenarios. The third pavement marking treatment level (PM3 = a skipped green bike lane with white outline) was found to have a significant effect on the crash outcome of being a near-collision or a collision.

Investigation of all incidents revealed that among 28 participants completing a total of 616 right turns, 20 were involved in 75 near-collision or collision incidents, with 44 (57%) of those incidents having a TTC value less than or equal to 1.5 seconds.

Concerning the signage treatments, the findings are unclear whether the S1 signage treatment appears to be an effective method of positively influencing driver behavior, with respect to crash avoidance.

There is no consistent pattern of change in crash avoidance between the level one and level zero signage treatment. The level one signage treatment showed a 7% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero signage treatment. However, the level one signage treatment showed a 3% higher cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero signage treatment

Concerning the pavement markings treatments, the findings indicate that the PM1, PM3, and PM4 pavement marking treatments appear to be an effective method of positively influencing the driver behavior, with respect to crash avoidance. It is unclear whether PM2 is an effective method.

There is a generally positive pattern of change in crash avoidance between the level one and level zero pavement marking treatment. The level one pavement marking treatment showed an 18% increase lower cumulative frequency of high risk TTCs, (equal to or less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Of the five pavement marking treatment levels, the presence of the level one pavement marking tied with the level three pavement marking treatment for the largest decrease in cumulative frequency of high-risk TTC values, in comparison to the level zero pavement marking treatment. Also, the level one pavement marking treatment showed a 15% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

There is no consistent pattern of change in crash avoidance between the level two and level zero pavement marking treatment. The level one pavement marking treatment showed a 12% higher cumulative frequency of high risk TTCs, (equal to or less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Of the five pavement marking treatment levels, the presence of the level two pavement marking treatment had the largest increase in cumulative frequency of high-risk TTC values. However, the level one pavement marking treatment showed a 4% lower cumulative frequency of high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

There is a generally positive pattern of change in crash avoidance between the level three and level zero pavement marking treatment. The presence of the level three pavement marking treatment had a statistically significant effect on the distribution of collisions and near-collisions, in comparison to the level zero pavement marking treatment (100% decrease in collisions and 18% decrease in near-collisions, with a p-value = 0.01). Also, the level three pavement marking treatment showed an 18% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero signage treatment. Of the five pavement marking treatment levels, the presence of the level three pavement marking tied with the level one pavement marking treatment for the largest decrease in cumulative frequency of high-risk TTC values, in comparison to the level zero pavement marking treatment. Also, the level three pavement marking showed a 2% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking.

There is a generally positive pattern of change in crash avoidance between the level four and level zero pavement marking treatment. The level four pavement marking treatment showed a

13% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Also, the level four pavement marking treatment showed a 12% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

Concerning the curb radii treatments, the findings indicate that the C1curb radii treatment appears to be an effective method of positively influencing driver behavior, with respect to crash avoidance.

There is a generally positive pattern of change in crash avoidance between the level one and level zero curb radii treatment. The level one curb radii treatment has the same cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero curb radii treatment. Additionally, the level one curb radii treatment showed a 7% lower cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero curb radii treatment.

Concerning the protected intersection treatments, the findings are unclear whether the PI1 or PI2 protected intersection treatments are effective methods of positively influencing driver behavior, with respect to crash avoidance.

There is no consistent pattern of change in crash avoidance between the level one and level zero protected intersection treatment. The level one protected intersection treatment showed a 19% lower cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero protected intersection treatment. Additionally, the level one protected intersection treatment showed a 5% higher cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero protected intersection treatment.

There is no consistent pattern of change in crash avoidance between the level two and level zero protected intersection treatment. The level two protected intersection treatment showed a 15% lower cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero protected intersection treatment. Additionally, the level two protected intersection treatment showed a 13% higher cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero protected intersection treatment. Also, the frequencies of both the moderate risk TTCs and high-risk TTCs were significantly lower than the level one protected intersection treatment (19 vs. 5 and 15 vs. 3, respectively).

13.0 RESULTS: EXPERIMENT 2 POTENTIAL CRASH SEVERITY

This chapter summarizes the analysis of the driving simulator output data that were collected while driving through the 22 right-turning intersections in the simulated environment of Experiment 2. The primary objective of this experiment is to determine the effect of the treatment levels on the velocity of the motorists when a near-collision or collision occurs with the bicyclist during a right-turn maneuver at a signalized intersection during the latter portion of the green phase. The chapter describes in more detail the experimental hypothesis for the potential crash severity component of the evaluation for Experiment 2.

13.1 DESCRIPTION OF EXPERIMENT

Higher velocities at the time of the traffic conflict are considered to be more severe, as injuries to the cyclist generally increase with higher velocities. We hypothesized that right-turning motorists' velocity at the time of collision or near-collision will be influenced by the treatments. The following hypothesis was formulated for each of the four treatment types:

- $H_{0\,(CS1)}$: The engineering treatments have no effect on the right-turning motorists' velocity at the time of near-collisions or collisions.

The motorist potential crash severity was assessed by performing descriptive statistics and statistical analysis in Microsoft Excel and R statistical software. As mentioned previously in Chapter 9 and Chapter 12, the driving simulator records dynamic variable data such as the subject vehicle and bicycle centroid, as well as the velocities of the subject vehicle. For Experiment 2 the 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 traffic conflicts that were classified in Chapter 12 as "moderate risk" or "high risk," according to the TTC values of the incident.

13.2 DESCRIPTIVE ANALYSIS

In this experiment, 28 participants each completed 22 right-turn maneuvers; in total, 616 right turns were made. Seventy-five total incidents were observed during 616 right turns (47 near-collisions and 28 collisions). Of these 75 incidents, 43 (57%) of them were classified as either "moderate risk" or "high risk," due to TTCs equal to or less than 1.5 seconds. Figure 13.1 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 13.1. 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.

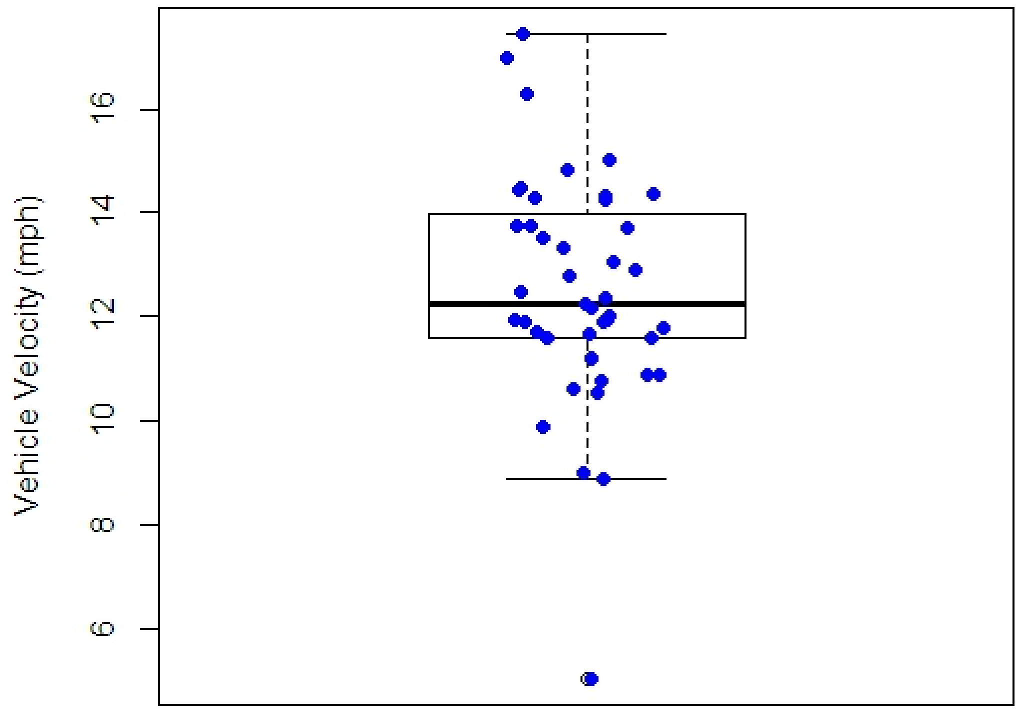


Figure 13.1: Boxplot and scatterplot of vehicle velocities for all moderate- & high-risk incidents

Table 13.1: Mean and range for vehicle velocities for all moderate- and high-risk incidents

Mean Velocity (mph)	Lower Range Value (mph)	Upper Range Value (mph)	Range (mph) *(Upper Value- Lower Value)*
12.70	8.88	17.45	8.57

13.2.1 Signage Treatments

Figure 13.2 displays a boxplot and scatterplot distribution of the vehicle velocities across all of the moderate- and high-risk incidents for the signage treatment levels: S0 and S1. 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 the calculation of the mean and range values of the vehicle velocities for this treatment level. The mean and range values for both signage treatment levels are summarized in Table 13.2.

The level one signage treatment has a slightly smaller mean vehicle velocity, in comparison to the level zero signage treatment (12.50 mph vs. 12.89 mph, a 3% decrease). However, the level one signage treatment also has a larger range of vehicle velocities, in comparison to the level zero signage treatment (8.57 mph range vs. 6.35 mph range, a 35% increase).

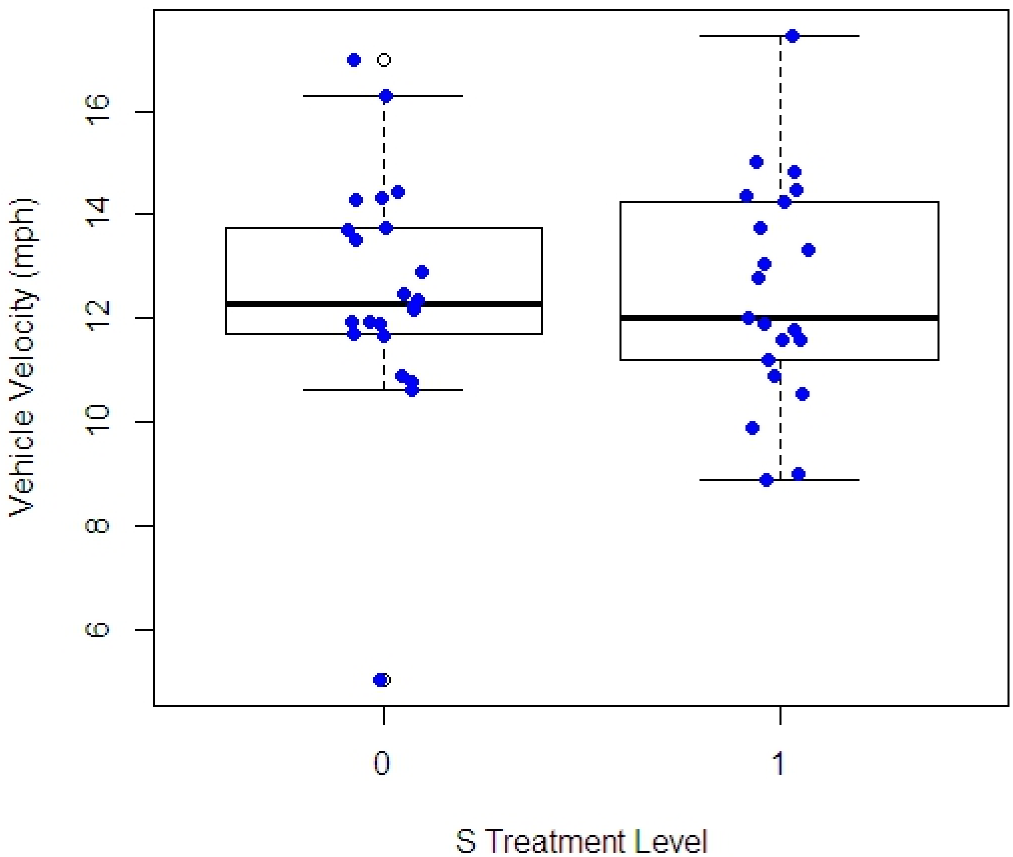


Figure 13.2: Boxplot and scatterplot of vehicle velocities for the signage treatment levels

Table 13.2: Mean and range for vehicle velocities for moderate- and high-risk incidents, S

Treatment	Mean Velocity (mph)	Lower Range Value (mph)	Upper Range Value (mph)	Range (mph) *(Upper Value- Lower Value)*
S0	12.89	10.63	16.98	6.35
S1	12.50	8.88	17.45	8.57

13.2.2 **Pavement Marking Treatments**

Figure 13.3 displays a boxplot and scatterplot distribution of the vehicle velocities across all of the moderate- and high-risk incidents for the pavement marking treatment levels: PM0, PM1, PM2, PM3, and PM4. As can be seen in the figure, there is a single outlier in the PM0 data (with a velocity equal to 5.03 mph). This outlier was removed for the calculation of the mean and range values of the vehicle velocities for this treatment level. The mean and range values for all pavement marking treatment levels are summarized in Table 13.3.

Three of the four treatments, (PM1, PM2, and PM3), have a larger mean vehicle velocity, in comparison to PM0 (12.99 mph, 13.03 mph, and 14.98 mph, respectively, vs. 12.24 mph). This equates to a 6% increase, a 6% increase, and a 22% increase, respectively, for PM1, PM2, and PM3, in comparison to PM0. The PM4 treatment has a smaller mean vehicle velocity, in comparison to PM0 (12.08 mph vs. 12.24 mph, a 1% decrease). The highest mean velocity for all of the pavement marking treatment levels is for PM3, at 14.98 mph.

With respect to the range of vehicle velocities, PM1 and PM4 have smaller ranges, in comparison to PM0 (3.94 mph range and 3.80 mph range vs. 6.15 mph range, respectively). This equates to a 36% decrease and a 38% decrease, respectively, for PM1 and PM4, in comparison to PM0. The PM2 and PM3 treatments have larger ranges of vehicle velocities, in comparison to PM0 (6.99 mph range and 6.24 mph range vs. 6.15 mph range, respectively). This equates to a 14% increase and a 1% increase, respectively, for PM2 and PM3, in comparison to PM0.

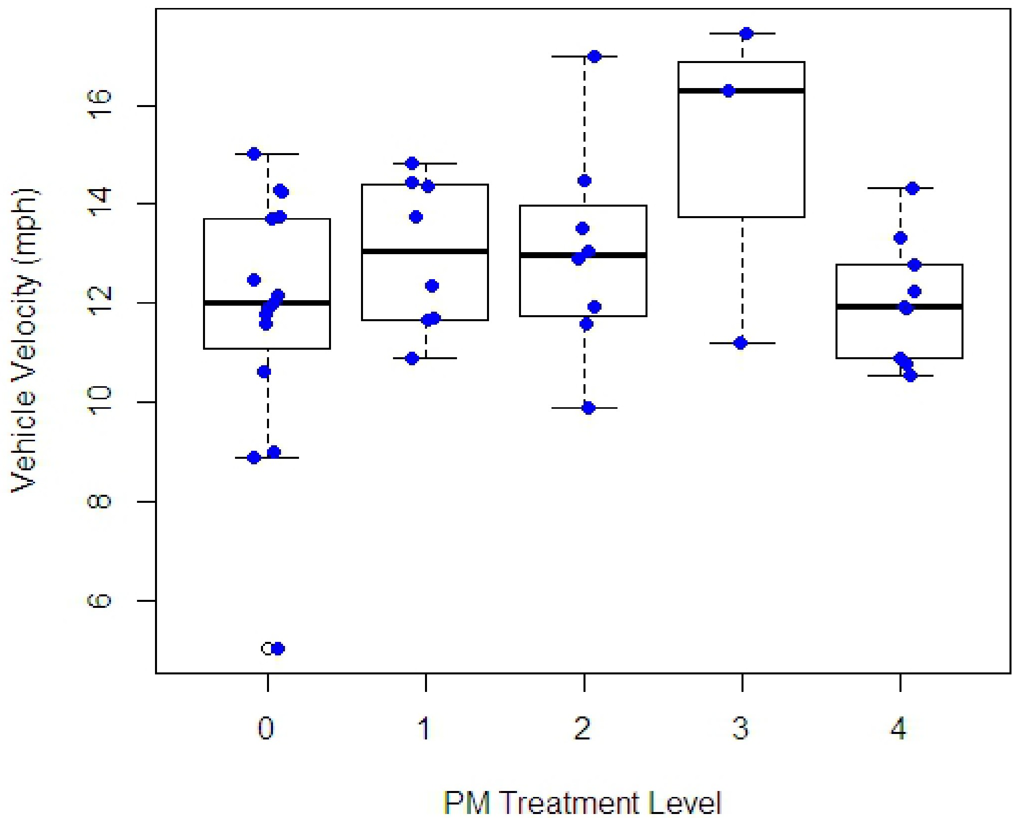


Figure 13.3: Scatterplot of vehicle velocities for the pavement marking treatment levels

Table 13.3: Mean and range for vehicle velocities for moderate- and high-risk incidents, PM

Treatment	Mean Velocity (mph)	Lower Range Value (mph)	Upper Range Value (mph)	Range (mph) *(Upper Value- Lower Value)*
PM0	12.24	8.88	15.03	6.15
PM1	12.99	10.87	14.81	3.94
PM2	13.03	9.99	16.98	6.99
PM3	14.98	11.21	17.45	6.24
PM4	12.08	10.54	14.34	3.80

13.2.3 Curb Radii Treatments

Figure 13.4 displays a boxplot and scatterplot distribution of the vehicle velocities across all of the moderate- and high-risk incidents for the curb radii treatment levels: C0 and C1. This treatment level is particularly important for the potential crash severity measurement, as lower curb radii generally require slower turning velocities, due to the impact of the physical forces involved in a turning maneuver. As can be seen in the figure, there is a single outlier in the C0 data (with a velocity equal to 5.03 mph). This outlier was removed for the calculation of the mean and range values of the vehicle velocities for this treatment levels. The mean and range values for both curb radii treatment levels are summarized in Table 13.4.

The level one curb radii treatment has a smaller mean vehicle velocity, in comparison to the level zero curb radii treatment (12.33 mph vs. 12.90 mph, a 4% decrease). In addition, the level one curb radii treatment has a smaller range of vehicle velocities, in comparison to the level zero curb radii treatment (3.71 mph range vs. 8.10 mph range, a 54% decrease).

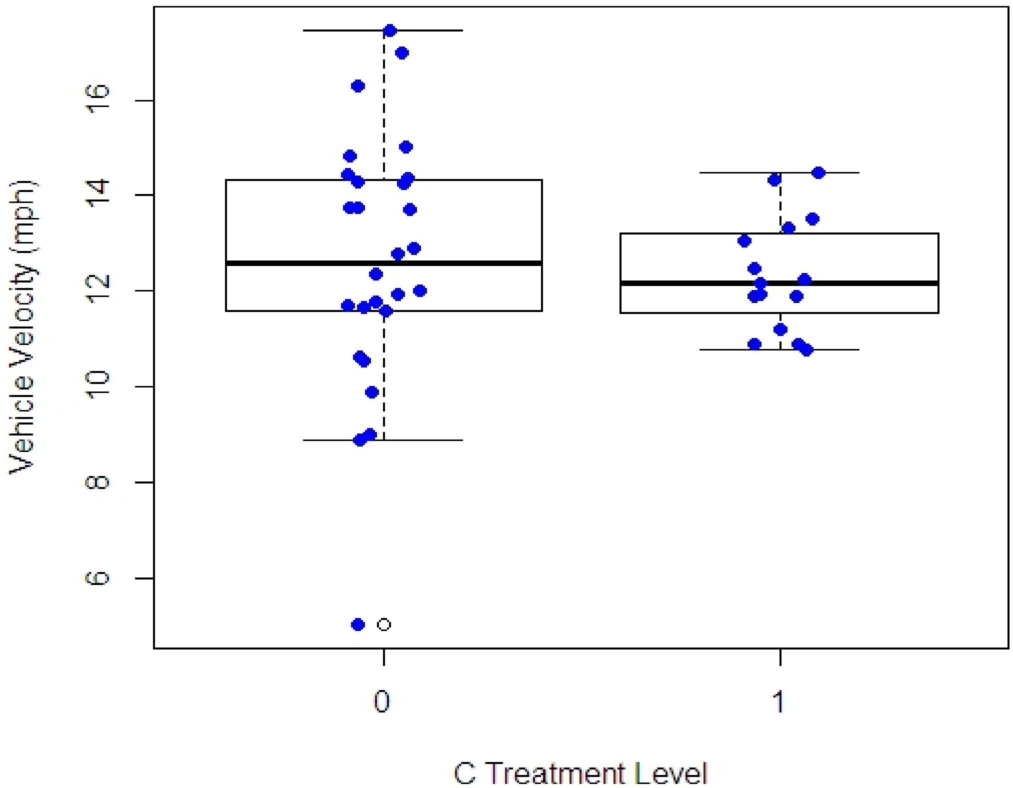


Figure 13.4: Scatterplot of vehicle velocities for the curb radii treatment levels

Table 13.4: Mean and range for vehicle velocities for moderate- and high-risk incidents, C

Treatment	Mean Velocity (mph)	Lower Range Value (mph)	Upper Range Value (mph)	Range (mph) *(Upper Value- Lower Value)*
C0	12.90	8.88	16.98	8.10
C1	12.33	10.76	14.47	3.71

13.2.4 Protected Intersection Treatments

Figure 13.5 displays a boxplot and scatterplot distribution of the vehicle velocities across all of the moderate- and high-risk incidents for the protected intersection treatment levels: PI0 (T1), PIO (T11), PI1, and PI2. It is important to note that the PI0 (T1) treatment only has a single moderate- to high-risk incident. It is also important to note that while there are technically no outliers for this data, the same low velocity value (5.03 mph) has been removed from the PI1 data for calculation of the means and ranges of the vehicle velocities, to be consistent with the other treatments. The means and ranges for all protected intersection treatment levels are summarized in Table 13.5.

The PI1 treatment has a smaller mean vehicle velocity, in comparison to PI0 (T1) (12.16 mph vs. 14.27 mph, a 15% decrease). The PI2 treatment has a smaller mean vehicle velocity, in comparison to PI0 (T11) (11.53 mph vs. 12.86 mph, a 10% decrease).

The impact of PI1 on the range of vehicle velocities could not be calculated, as the PI0 (T1) has only a single moderate- to high-risk incident. However, the PI2 treatment has a much larger range of vehicle velocities, in comparison to PI0 (T11) (5.37 mph range vs. 3.47 mph range, a 55% increase).

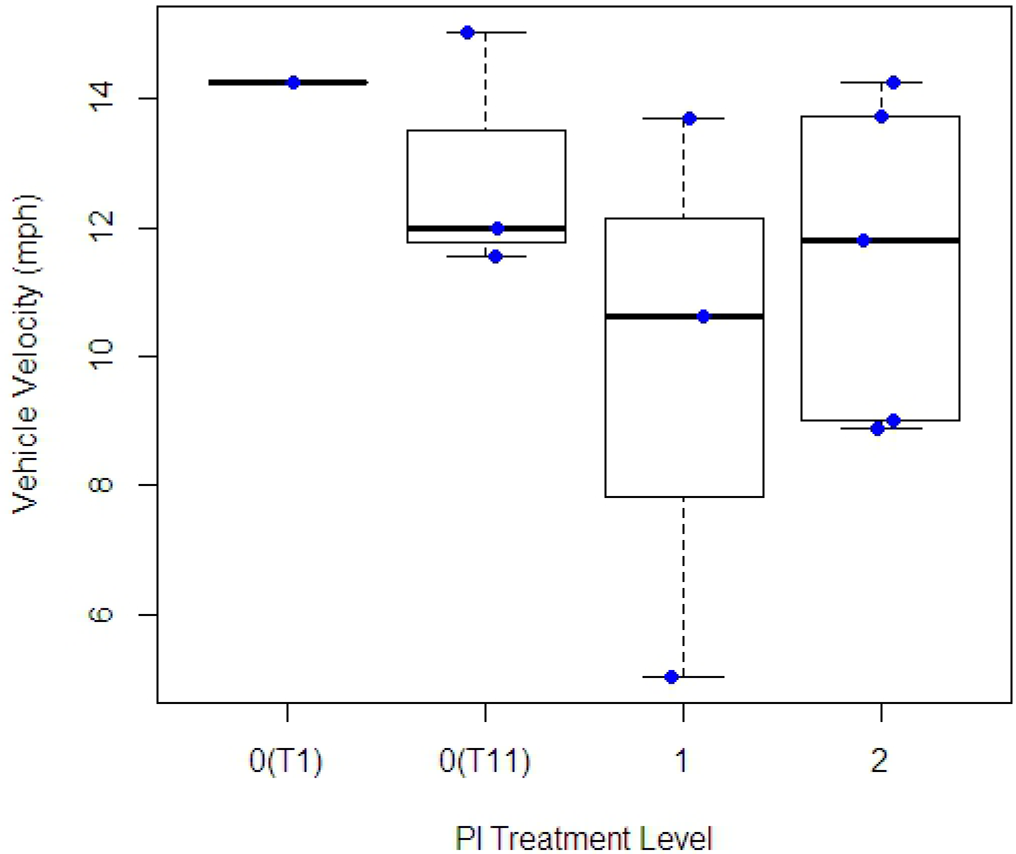


Figure 13.5: Scatterplot of vehicle velocities for the protected intersection treatment levels

Table 13.5: Mean and range for vehicle velocities for moderate- and high-risk incidents, PI

Treatment	Mean Velocity (mph)	Lower Range Value (mph)	Upper Range Value (mph)	Range (mph) *(Upper Value- Lower Value)*
PI0 (T1)	14.27	NA	NA	0
PI0 (T11)	12.86	11.56	15.03	3.47
PI1	12.16	10.63	13.69	3.06
PI2	11.53	8.88	14.25	5.37

13.3 STATISTICAL ANALYSIS

A two-sample Welch's t-test was performed for all of the treatment types and their levels. These tests compared the vehicle velocities for the "base" condition to the vehicle velocities for the treatment condition, to determine whether there is a significant difference between the values of each. Additionally, analysis of variance was also used to statistically determine if there is a significant difference between the vehicle velocities of the base and treatment conditions. Table 13.6 presents the results of these two tests.

The two-sample Welch's t-test and the ANOVA analysis did not result in any statistically significant differences between any of the treatment levels and their associated "base" conditions, as measured by vehicle velocities at time of the incident, with 95% confidence.

Table 13.6: Statistical analysis tests for vehicle velocities at moderate- and high-risk incidents

Treatment Level Comparisons		Vehicle Velocities		ANOVA	Welch's Two sample two tail *t*-test		
					Level A vs. Level B		
Level A	Level B	Level A	Level B	p-value	p-value	Sig	Diff
S0	S1	12.53	12.50	0.96	0.96	No	-0.03
PM0	PM1	11.76	12.99	0.17	0.17	No	1.23
PM0	PM2	11.76	13.03	0.22	0.22	No	1.27
PM0	PM3	11.76	14.98	0.23	0.23	No	3.22
PM0	PM4	11.76	12.08	0.69	0.69	No	0.32
C0	C1	12.62	12.33	0.63	0.63	No	-0.29
PI0 (T1)	PI1	14.27	9.78	N/A**	N/A**	N/A**	-4.49
PI0 (T11)	PI2	12.86	11.53	0.43	0.43	No	-1.33
PI1	PI2	9.78	11.53	0.58	0.58	No	1.75

**PI0 (T1) has only one moderate- to high-risk incident, so the Welch's & ANOVA statistical tests could not be performed for the PI0 (T1) - PI1 treatment level comparison

13.4 SUMMARY

The impact of the treatments on potential crash severity was assessed by analyzing the vehicle velocities at the time of incidents that were classified in Chapter 12 as "moderate risk" or "high risk," according to the TTC values of the incident. Higher velocities at the time of the traffic conflict are considered to be more severe, as injuries to the cyclist generally increase with higher velocities.

While there were no statistically significant differences between the treatment levels, the differences in mean vehicle velocities and range of vehicle velocities between the treatment levels is indicative of the treatment impacts on potential crash severity. The findings are summarized below:

Concerning the signage treatments, the findings are unclear whether the S1 signage treatment appears to be an effective method of positively influencing driver behavior, with respect to crash severity.

There is no consistent pattern of change in potential crash severity between the level one and level zero signage treatments. The level one signage treatment showed a small 3% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero signage treatment. However, the level one signage treatment also showed a 35% larger range of vehicle velocities, in comparison to the level zero signage treatment.

Concerning the pavement markings treatments, the findings indicate that the PM4 treatment does appear to be an effective method of positively influencing the driver behavior, with respect to crash severity. They also indicate that the PM2 and PM3 treatments do not appear to be an effective method. It is unclear whether PM1 is an effective method.

There is no consistent pattern of change in potential crash severity between the level one and level zero pavement marking treatments. The level one pavement marking treatment showed a 6% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. However, the level one pavement marking treatment also showed a 36% smaller range of vehicle velocities, in comparison to the level zero pavement marking treatment.

There is a generally negative pattern of change in potential crash severity between the level two and level zero pavement marking treatments. The level two pavement marking treatment showed a 6% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. Additionally, the level two pavement marking treatment also showed a 14% larger range of vehicle velocities, in comparison to the level zero pavement marking treatment.

There is a generally negative pattern of change in potential crash severity between the level three and level zero pavement marking treatments. The level three pavement marking treatment showed a 22% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. The level three pavement marking has the highest mean velocity of all pavement marking treatment levels. Additionally, the level three pavement marking treatment also showed a 1% larger range of vehicle velocities, in comparison to the level zero pavement marking treatment.

There is a generally positive pattern of change in potential crash severity between the level four and level zero pavement marking treatments. The level three pavement marking treatment showed a 1% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. Additionally, the level four pavement marking treatment also showed a 38% smaller range of vehicle velocities, in comparison to the level zero pavement marking treatment.

Concerning the curb radii treatments, the findings indicate that the C1 curb radii treatment appears to be an effective method of positively influencing driver behavior, with respect to crash severity.

There is a generally positive pattern of change in potential crash severity between the level one and level zero curb radii treatments. The level one curb radii treatment showed a 4% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero curb radii treatment. Additionally, the level one curb radii treatment showed a 54% smaller range of vehicle velocities, in comparison to the level zero curb radii treatment. This finding of lower speeds for the smaller radii is a clear benefit and is consistent with the formulaic relationship between the design speed and the minimum radius of curvature, found in the AASHTO "A Policy on Geometric Design of Highways and Streets" *(AAHSTO 2011).*

Concerning the protected intersection treatments, the findings indicate that the PI1 protected intersection treatment appears to be effective methods of positively influencing driver behavior, with respect to crash severity. It is unclear whether PI2 is an effective method.

There is a generally positive pattern of change in potential crash severity between the level one and level zero protected intersection treatments. The level one protected intersection treatment showed a 15% decrease in the mean velocity during moderate- to high-risk incidents, in comparison to the level zero protected intersection treatment. The impact of the level one protected intersection treatment on the range of vehicle velocities was unable to be calculated.

There is no consistent pattern of change in potential crash severity between the level two and level zero protected intersection treatments. The level two protected intersection treatment showed a 10% decrease in the mean velocity during moderate- to high-risk incidents, in comparison to the level zero protected intersection treatment. However, the level two protected intersection treatment showed a 55% larger range of vehicle velocities, in comparison to the level zero protected intersection treatment.

14.0 RESULTS: EXPERIMENT 2 SURVEY

This chapter summarizes the descriptive analysis of the participants' follow-up survey response data that were collected with online Qualtrics survey software following the driving simulator portion of Experiment 2.

14.1 DESCRIPTION OF EXPERIMENT

The primary objective of this experiment is to determine motorist perceptions of the selected engineering treatments and their visual attention, with respect to an adjacent bicyclist. A secondary objective of this descriptive analysis is to determine motorist perceptions of a treatment that was unable to be tested within the simulated environment: the dynamic "Turning Vehicle Yield to Bikes" traffic sign.

14.2 DESCRIPTIVE ANALYSIS

This analysis highlights some of the follow-up survey response findings in more detail; specifically: comprehension and preference of the pavement marking treatments, comprehension of the protected intersection treatments, comprehension of the dynamic traffic sign, and the visual attention of the motorist, with respect to adjacent bicyclists.

14.2.1 Comprehension and Preference of Pavement Marking Treatments

The pavement marking treatment type includes five treatment levels: PM0, PM1, PM2, PM3, and PM4. Because of this additional complexity, the follow-up survey included questions to assess the perceptions and preferences of the pavement marking treatment levels.

Figure 14.1 shows the first question, which assessed the driver perceptions of the difference between two green pavement marking levels: PM3 and PM4. Table 14.1 shows the participant responses to this question. These responses revealed that 61% of participants felt that the skipped green pavement marking is not the same as the solid green pavement marking. The reasoning they provided for how they were different included statements about how the skipped green indicates a yielding condition for the bicyclist and the solid green indicates a right-of-way for the bicyclist. Others stated that the skipped green pavement marking created confusion between the vehicle and bicyclist access.

The second question assessed which of the five pavement marking levels the drivers preferred. Figure 14.2 shows a summary of the participant responses to this question. These responses revealed that 50% of participants preferred the level two pavement marking treatment. Table 14.2 reveals the frequencies of driver preferences across the five levels. It is interesting to note that when the responses are broken down by gender, the distributions of the pavement marking treatment preferences change. The male participants preferred the level four pavement marking treatment over the level two pavement marking treatment (44% to 39%). In contrast, the female participants preferred the level two pavement marking treatment over the level four pavement marking treatment (70% to 20%). It is unclear why the male and female participants had different treatment preference distributions.

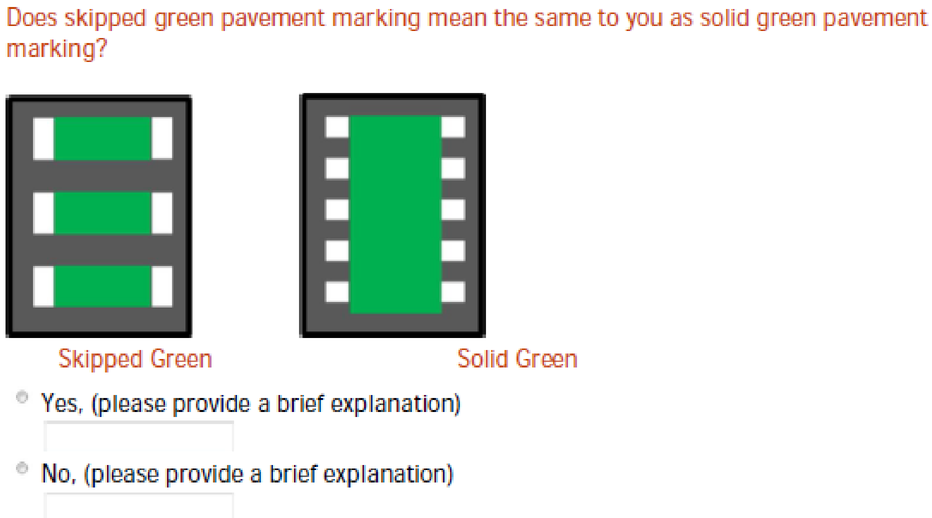


Figure 14.1: Qualtrics survey question for assessing self-reported comprehension of the difference between level three pavement marking and level four pavement marking

Table 14.1: Participant perception on difference between the level three pavement marking and level four pavement marking

Question	Possible Responses	Number of Participants	Percentage of Participants
Does skipped green pavement marking mean the same to you as solid green pavement marking?	Yes	11	39%
	No *“I get the impression that striped green implies some kind of complication in yield, where solid green means bikes”* *“Skipped green would mean that you are able to pass through it like at an intersection.”* *“skipped means cars may be passing through the area (an indicator for cyclists) AND that it's a bike lane (for drivers)”* *“skipped could confuse between car & bike access”*	17	61%

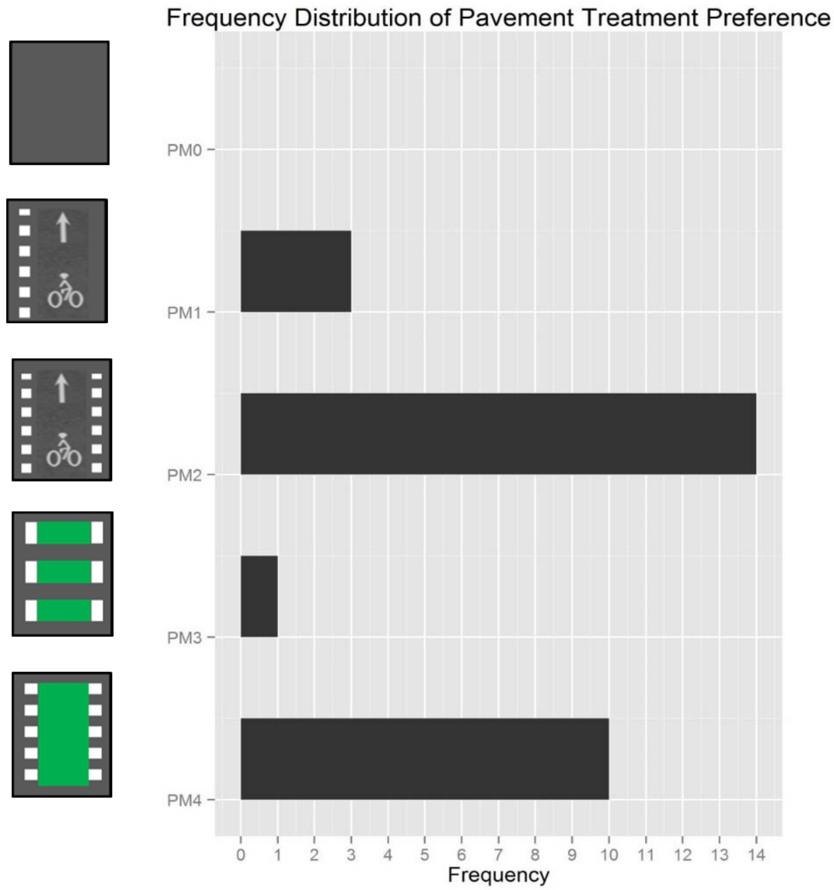


Figure 14.2: Qualtrics survey question for assessing preference of pavement marking treatment levels

Table 14.2: Frequency of driver preferences for pavement marking treatment levels

Treatment Preference	Frequency (% of Total)		
	Male	Female	Total
PM0	0	0	0
PM1	2 (11%)	1 (10%)	3 (11%)
PM2	7 (39%)	7 (70%)	14 (50%)
PM3	1 (6%)	0	1 (4%)
PM4	8 (44%)	2 (20%)	10 (36%)
Total	18	10	28

14.2.2 **Comprehension of Protected Intersection Treatments**

Protected intersection treatments have only recently been introduced into the U.S (only one known installation; more planned). Because of this, there are concerns that the U.S. driver population would have some challenges in comprehending the correct vehicle path (which is shown below in Figure 14.3 as the green arrow path). Within Experiment 2, each of the 28 participants drove through two protected intersections, resulting in 56 right-turn maneuvers through protected intersections. Of those 28 participants and 56 right-turn maneuvers, 12 participants took the wrong path in 17 (30%) of those maneuvers.

Table 14.3 shows the frequencies of incorrect and correct paths for the PI1 and PI2 treatment levels, as well as the total frequencies of all protected intersection treatments. The level one protected intersection treatment has a 3% higher frequency of incorrect paths taken, in comparison to the level two protected intersection treatment (32% vs. 29%).

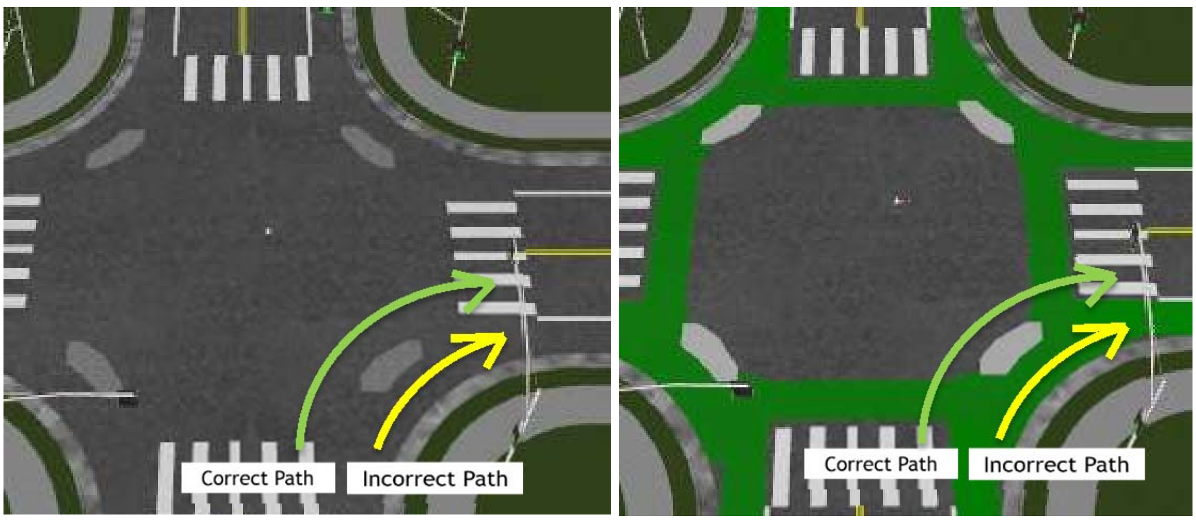


Figure 14.3: Motorist path in the protected intersection treatments (correct path = green arrow, and incorrect path = yellow arrow)

Table 14.3: Frequency of incorrect paths within the protected intersection treatments

Motorist Path	Frequency (% of Total)		
	PI1	PI2	Total
Incorrect	9 (32%)	8 (29%)	17 (30%)
Correct	19 (68%0	20 (71%)	39 (70%)
Total	28	28	56

The follow-up survey included a question to assess the self-reported driver comprehension of the protected intersection treatments: “If you were a driver approaching an intersection (like the two below) and you were wanting to turn right…would you understand the path that your vehicle would need to take?” The formatting and images for this question are shown in Figure 14.4.

Table 14.4 shows the frequency of responses for the self-reported driver comprehension of the protected intersection treatments. Additionally, Table 14.4 also benchmarks these participant responses against the observed driver behavior, with respect to correct/incorrect paths. Of the 28 participants, 25% of the participants reported that they would not understand the correct vehicle path for a protected intersection; however, 43% of the participants took the incorrect path. This indicates that driver comprehension is being over-reported. Eight (29%) of the participants stated they would understand the path they would need to take, but actually took the incorrect motorist path while driving through at least one of the two protected intersection treatments. This finding suggests that 29% of drivers would incorrectly comprehend the path they would need to take, and that the design may not be intuitive to nearly one-third of all drivers.

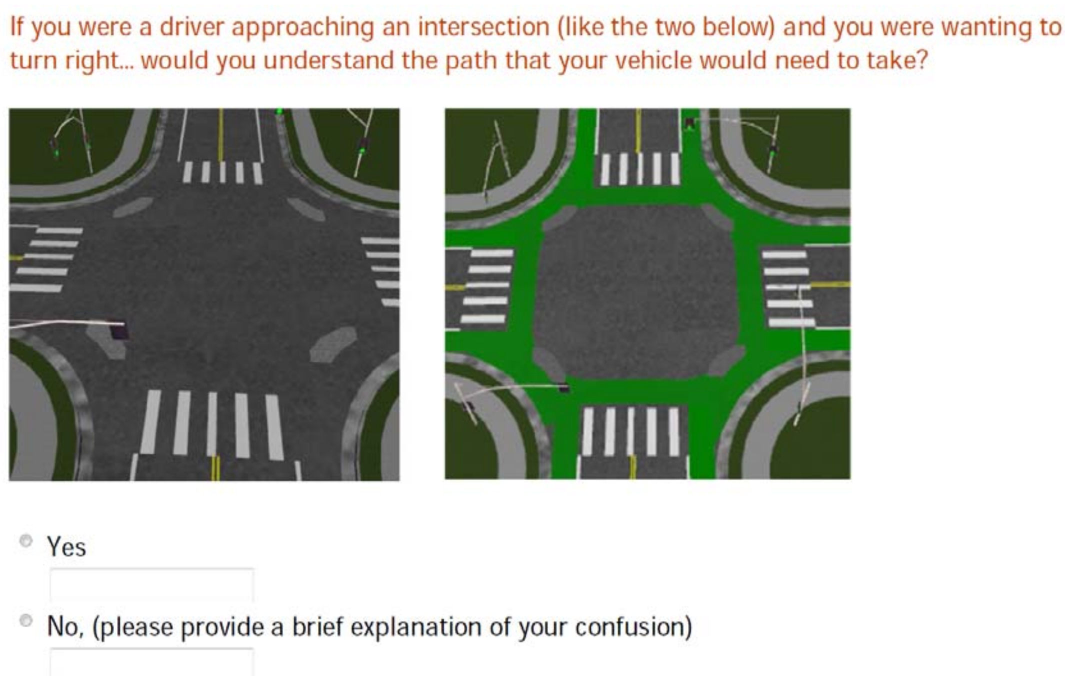


Figure 14.4: Qualtrics survey question for assessing self-reported comprehension of protected intersection treatments

Table 14.4: Reponses to Qualtrics survey question for self-reported comprehension of protected intersection treatment, compared to observed motorist behavior

Question	Possible Responses	Number of Participants (% of Total)	Correct Motorist Path Taken (% of 28)	Incorrect Motorist Path Taken (% of 28)
Would you understand the path that your vehicle would need to take?	Yes	21 (75%)	13 (46%)	8 (29%)
	No	7 (25%)	3 (11%)	4 (14%)
	Total:	28	16 (57%)	12 (43%)

In addition to answering "yes" or "no" to self-report their comprehension of the protected intersections, drivers were also provided the opportunity to provide an explanation for why they did or did not understand the correct vehicle path. A few of the correct comprehension statements included: "bikes are in the area and to be careful and watchful for them," "a car turns around the cement blocks," and "don't turn into the bike lane area." Some of the participants stated their confusion between the two treatment levels, with one participant stating: "I don't get the difference between the green and non-green pavement markings."

Table 14.5 summarizes some of the driver explanations and a few of the specific responses for drivers who felt that the level two protected intersection treatment (with the islands and the pavement marking) is less confusing than the level one protected intersection treatment (with just the islands), and a few of the responses for the drivers who felt that the level two protected intersection treatment was more confusing than the level one protected intersection treatment.

Table 14.5: Driver explanations related to protected intersection treatment comprehension

Theme	Explanations
PI2 less confusing than PI1	*"the one on the left is not as clear as the one on the right"* *"better with the green, highlights the pinch to your turn radius from the curb islands"* *"the small island (without the green lane marking) is mildly confusing"* *"the green lane marking clarifies this, indicating it's intended for bicycles"*
PI1 less confusing than PI2	*"Green is kind of distracting"* *"the left one is clear but the intersection with green is confusing"* *"At first I didn't even notice the green path, but then I thought it was meant for my car. Now I realize it was probably meant for bicycles"* *"At first I wouldn't know where to turn because of the green markings on top of the things on the side"*

It is important to note that the protected intersection treatment considered within Experiment 2 utilized a specific geometric design and specific pavement markings. Clearly it would be possible to improve these design elements and potentially mitigate these "correct path" comprehension issues.

14.2.3 Comprehension of Dynamic Sign

The dynamic "Turning Vehicle Yield to Bikes" traffic sign has been implemented by the City of Portland. Figure 14.5 shows the two phases of the dynamic "Turning Vehicle Yield to Bikes" traffic sign, which is currently in use in the Portland metropolitan area. This sign flashes back and forth between these phases when a bicyclist is present at the intersection.

a.) sign dark

b) sign activated

c) flashing yield triangle and arrow growing bottom to top

Figure 14.5: Sequence of the dynamic “Turning Vehicle Yield to Bikes” sign

Due to the design limitations of the simulated environment, the dynamic “Turning Vehicle Yield to Bikes” traffic sign was not included in simulated environment. While the effectiveness of this sign could not be assessed using the visual attention, crash avoidance, or potential crash severity performance measures, the driver comprehension could be assessed by including it within the follow-up survey. Participants were shown a 2-second video of the traffic sign during the follow-up survey. After the video, the following two open-ended questions were presented to the participants: 1) “What does this traffic sign mean to you?” and 2) “If you were to encounter this traffic sign at a signalized intersection as a driver and you were wanting to turn right, what would you do?” The responses to both questions were classified as “correct,” “partially correct,” “non-critical incorrect,” and “critical incorrect” based on criteria unique to each question.

14.2.3.1 What does this sign mean to you?

The majority of the responses for this open-ended question mentioned that the turning vehicle should yield to bicyclists. Table 14.6 shows the classification criteria and the breakdown of the responses into the four categories of “correct,” “partially correct,” “non-critical incorrect,” and “critical incorrect,” as well as a few specific responses. Seventy-five percent of the responses were “correct,” indicating that the participants generally understood that the sign was indicating that the turning vehicle should yield to bike.

There were some very significant “critical incorrect” responses. For one of these, the participant thought the sign was indicating that the bicyclist should yield to the turning vehicle. This understanding is clearly problematic in that it produces driver behavior that is opposite to what is desired. The other “critical incorrect” responses were classified as such because they referred to the bicyclist as the “oncoming bicyclist,” which technically is not the same as the adjacent bicyclist. The participant could have been confused with the proper naming convention, but if they did think that the sign was related to the oncoming bicyclist (instead of the adjacent) the participant could have failed to search for and identify an adjacent bicyclist, increasing the likelihood of a right-hook crash. Table 14.7 summarizes the general themes in the responses.

Table 14.6: Classification of correctness for open-ended responses

Classification	Criteria	Number of Participants	Percentage
Correct	Included mention that the turning vehicle should yield to the bicyclist.	21	75%
Partially Correct	Included mention of looking for the bike or proceeding cautiously, but failed to mention that the vehicle should yield to the bicyclist.	3	11%
Non-Critical Incorrect	Included mention of behavior that shouldn't increase the likelihood of a right-hook crash.	0	0%
Critical Incorrect	Included mention of behavior that should increase the likelihood of a right-hook crash. *"Yield to bikers that may be turning left"* *"Bikes must yield to cars turning at the intersection"* *"Yield to oncoming bikes"* *"There are oncoming bikers so if you're turning right make sure to yield to them."*	4	14%

Table 14.7: General themes for dynamic traffic sign open-ended responses, question 1

General Trends	Number of Participants	Percentage
Look for Bikes	4	14%
Car Yields to Bicyclists	24	86%
Slow Down	1	4%

14.2.3.2 If you were to encounter this traffic sign at a signalized intersection as a driver and you were wanting to turn right, what would you do?

The majority of the responses for this open-ended question mentioned that the turning vehicle should yield to bicyclists. Table 14.8 shows the classification criteria and the breakdown of the responses into the four categories of "correct," "partially correct," "non-critical incorrect," and "critical incorrect," as well as a few specific responses. Thirty-six percent of the responses were "correct," indicating that the participants generally understood that the sign was indicating that the turning vehicle should yield to bike. The two "critical incorrect" responses were classified as such because they referred to the bicyclist as the oncoming bicyclist. The participant could have been confused with the proper naming convention, but if they did think that the sign was related to the oncoming bicyclist (instead of the adjacent) the participant could have failed to search for and identify an adjacent bicyclist, increasing the likelihood of a right-hook crash. Table 14.9 summarizes the general themes in the responses. Thirty-two percent of the responses mentioned that they should be checking the mirrors, 25% mentioned that they should look right, and 21% percent of the responses mentioned that they should slow down.

It is important to also note that many older participants (55+) asked to see the 2-second video many more times than younger participants. Younger participants asked to see it once or twice, whereas older drivers asked to see it upwards of three or four times. This is significant in that it may pull too much of the driver's visual attention while they are trying to understand the message of the sign, and detract from the visual attention that the driver gives to scanning for the bicyclist.

Table 14.8: Classification of correctness for dynamic traffic sign open-ended responses

Classification	Criteria	Number of Participants	Percentage
Correct	Included mention that the turning vehicle should yield to the bicyclist.	10	36%
Partially Correct	Included mention of looking for the bike or proceeding cautiously, but failed to mention that the vehicle should yield to the bicyclist. *"Check my mirrors to make sure no bikers are coming through the intersection"* *"double check blind spot"*	15	54%
Non-Critical Incorrect	Included mention of behavior that shouldn't increase the likelihood of a right-hook crash. *"stop"*	1	4%
Critical Incorrect	Included mention of behavior that should increase the likelihood of a right-hook crash. *"Check for an oncoming bikers"* *"Slow down and check for oncoming bikers then proceed slowly to make my right-turn"*	2	7%

Table 14.9: General themes for dynamic traffic sign open-ended responses, question 2

General Trends	Number of Participants	Percentage of Participants
Check mirrors	9	32%
Look Back	4	14%
Look Right	7	25%
Slow Down	6	21%
Yield to Bicyclists	10	36%
Check Blind Spot	4	14%

14.2.4 Visual Attention of Motorist

The participants were asked to assess their typical visual attention when performing a right-turn maneuver at an intersection, specifically how often they look for bicyclists adjacent to or behind their vehicle. Table 14.10 summarizes the frequency of participant responses for the four options: “Never,” “Rarely,” “Often,” and “Always.” Combined, 71% of participants reported that they either “always” or “often” look for bicyclists in those positions during the right-turn maneuver.

Table 14.10: Frequency of motorist fixation on bicyclist before turning right

Question	Possible Responses	Number of Participants	Percentage of Participants
How often do you look for bicyclists adjacent-to or behind your vehicle when performing a right-turn at an intersection?	Never	0	0%
	Rarely	8	29%
	Often	9	32%
	Always	11	39%

14.3 SUMMARY

The descriptive statistics of the follow-up survey results indicate that the level two pavement marking treatment is the most preferred of the five pavement marking treatment levels.

Additionally, the self-reported protected intersection comprehension results indicate that in 30% of the protected intersection right-turn maneuvers the drivers took the incorrect path. The level one protected intersection treatment had a 3% lower frequency than the level two protected intersection treatment. Forty-three percent of the drivers took the incorrect path through at least one of the two protected intersections during Experiment 2.

Concerning the dynamic traffic sign, 75% correctly assessed the meaning of the sign and 14% critically incorrectly assessed the meaning of the sign. Additionally, 36% of drivers projected that they would execute appropriate yield behavior, and 7% of drivers projected that they would execute critically incorrect driver behavior.

Concerning the self-reported visual attention results, a combined 71% of participants reported that they either “always” or “often” look for bicyclists in those positions during the right-turn maneuver.

15.0 CONCLUSIONS

The overall goal of the research was to quantify the safety performance of alternative traffic control strategies to mitigate right-turning vehicle-bicycle crashes at signalized intersections in Oregon. The ultimate aim was to provide useful design guidance to potentially mitigate these collision types at the critical intersection configurations. Thus, the objectives of the research were:

1. To comprehensively analyze the literature and to develop an understanding of the known crash mechanisms;

2. To analyze Oregon crash records and to develop an understanding of the frequency of the crash problem at Oregon intersections and guide the design of the simulator experiment;

3. To address the identified gaps in the literature and develop a fundamentally better understanding of driver and bicyclist interactions during right-turning events at signalized intersections in a driving simulator;

4. To validate the driver performance and gap selection in the driving simulator with field observations; and

5. To evaluate potential design treatments through the observation of driver performance in a driving simulator.

To accomplish these objectives the research team followed a robust research plan. First, a comprehensive review of more than 150 scientific and technical articles was performed. Then a total of 504 potential right-hook crashes were identified in the reported Oregon crash data from 2007-2011. Based on these efforts, a two stage experiment was developed in the OSU high-fidelity driving simulator to investigate the causal factors of right-hook crashes, and to then identify and evaluate alternative design treatments that could mitigate the occurrence of right-hook crashes.

The first simulator experiment aimed to uncover and measure the key crash mechanisms as they relate to driver performance. The experiment measured driver visual attention, situational awareness, and crash avoidance behavior across a carefully counterbalanced set of scenarios. A total of 51 participants completed the simulated driving environment making a total of 820 right-turns. The experiment identified a set of factors that appeared to be critical to the observed crash outcomes. To validate the driver performance measures obtained in the driving simulator, 144 hours of video data were recorded in the field and compared to the simulated driving measures. In the second simulator experiment, a carefully selected set of design treatments, (that included traffic signs, pavement markings, curb-radii, and a protected intersection design), were evaluated by comprehensively measuring the driver performance of an additional 28 subjects making 596 right-turns in another careful counterbalanced and designed experiment. Finally, subjects in the last experiment were asked preference and comprehension questions about the potential design treatments.

The following sections summarize and synthesize the conclusions for each of the five research objectives. The closing sections present the limitations and recommendations for future work and, most importantly, the suggestions of recommended practice for signalized intersection designs involving right-turning vehicles and through-moving cyclists.

15.1 LITERATURE REVIEW

The literature review revealed that although right-hook crashes have received significant attention, no robust experimental evidence exists proving the factors contributing to right-hook crashes. This research effort filled that gap by exploring the causal factors of right-hook crashes. The significance of this research is that it presents an expanded understanding of right-hook crash causal factors by combining the disciplines of traffic engineering and transportation human factors.

15.2 ANALYSIS OF POTENTIAL RIGHT-HOOK CRASHES IN OREGON

The research reviewed 504 potential right-hook crashes identified from vehicle movement data out of the 4,072 total crashes identified in ODOT reported crash data (*ODOT 2011*). These crashes with a right-turning motor-vehicle and through bicyclist accounted for 12.3% of all bicycle-related crashes during this time period. Though it is a frequent crash type, the majority of recorded crashes were moderate (62%) severity. A further 28% were minor injury and 4% were no injury. Still, 7% of the crashes were severe or fatal injury and represent and opportunity to improve safety for bicyclists. Each right-hook crash was reviewed in detail to identify the type of intersection traffic control and lane configurations. Intersection locations accounted for 74% of right-hook crashes; the remaining 26% of crashes occurred at driveways. The most common intersection configuration for these crashes was a bike lane adjacent to the through motor vehicle lane with no right-turn lane. This configuration accounted for 59% of total crashes at signalized intersections and 64% of total crashes at minor stop intersections.

15.3 CRASH CAUSATION MECHANISMS

The first driving simulator experiment investigated motorist and environmental related causal factors of right-hook crashes, using three different motorist performance measures: 1) visual attention, 2) SA, and 3) crash avoidance behavior. As such, the driving simulator experiment was divided into three components to address specific sets of research questions associated with each performance measure. All performance measures were assessed during right-turn maneuvers that occurred during the latter portion of the green phase at signalized intersections. This section summarizes the findings from each component of the first driving simulator experiment.

15.3.1 **Visual Attention**

Motorists' visual attention was investigated during 20 right-turning scenarios with bicycle traffic using head-mounted eye-tracking technology. The research objective was to investigate whether motorists actively search for bicyclists before turning right and to examine the influence of various adjacent traffic configurations, such as a pedestrian in the conflicting crosswalk and oncoming vehicles, on motorists' visual attention. The average total fixation durations (ATFD), measured in seconds, within a prescribed AOI was used to measure motorists' visual attention on different targets. Findings related to motorists' visual attention include:

- The ATFDs on an adjacent bicyclist between the scenario where a bicyclist was approaching from behind and the scenario where a bicyclist was riding ahead of the motorist were statistically different (p-value <0.001). A statistically significant difference (p-value < 0.001) was also observed between the frequencies of motorist fixations on the bicyclist when the bicyclist was approaching from behind (44%) vs. when bicyclist was riding ahead (87%). Such scanning behavior places bicyclists approaching from behind in a more vulnerable situation where they are not detected by a motorist at an intersection, contributing to the occurrence of right-hook crashes.

- The ATFDs on the conflicting pedestrian (p-value = 0.039) and oncoming vehicles (p-value = 0.002), with respect to bicyclist's position, were statistically significant. This finding suggests that in the absence of the bicyclist in the focal vision, i.e. when the bicyclist was approaching from the behind, motorists spent more time fixating on other traffic elements immediately relevant to the safe operation of the vehicle.

- A statistically significant finding (p-value = 0.049) was observed in the ATFDs on the right-side mirror when the bicyclist was approaching from behind compared to when there was no bicyclist. This suggests that when a bicyclist approaching from behind was detected in the right side mirror, the motorist spent more time fixating on the right-side mirror while waiting for the bicyclist to pass at the intersection as compared to when there was no bicyclist present.

- Bicyclist's speed had a statistically significant effect on the ATFDs directed at the rear view mirror (p-value = 0.03), indicating that the total fixation duration on the rear view mirror in search of bicyclist was higher when the bicyclist traveled at a lower speed. This result is intuitive as the cyclist is visible in the mirror for a longer time at a lower speed.

- Statistically significant differences in the ATFDs were found for crossing pedestrians (p-value < 0.001), side traffic signal (p-value = 0.02) and bicyclist riding ahead of the motorist (p-value = 0.01) between all intersections with the presence of oncoming vehicular traffic vs. no oncoming vehicular traffic. Results suggest that in the presence of oncoming vehicular traffic, motorists spent the majority of their visual attention looking at the most significant hazards in their forward vision, i.e. oncoming left-turning traffic. These findings are consistent with previous findings of Hurwitz et al., Knodler and Noyce, and Summala et al. (*Hurwitz et al. 2013; Knodler and Noyce 2005; Summala et al. 1996*).

- The presence of a pedestrian had a statistically significant effect on the ATFDs of a bicyclist approaching from behind the motorist (p-value <0.001). Results suggest that when a conflicting pedestrian was in the motorists' focal vision, motorists spent more time fixating on the pedestrian and failed to fixate on the bicyclist that was approaching from behind in the blind spot.

15.3.2 **Situational Awareness**

Motorists' three levels of SA, i.e. Level 1 SA (perception), Level 2 SA (comprehension), Level 3 SA (projection) and the overall SA were measured immediately after six right-turning scenarios. The objective was to investigate if right-turning motorists were able to monitor adjacent traffic and use that knowledge to avoid collisions. SA findings are listed below.

- *The relative position of an adjacent bicyclist significantly influenced right-turning motorists' overall SA (*p-value = 0.002) and Level 2 SA (p-value = 0.016). Participant's overall and Level 2 SA scores were lower when bicyclists were approaching from behind rather than riding ahead of the motorist. This finding reinforces the findings of Gugerty, Falzetta, and Crundall et al., who summarized that motorists focus the majority of their attention on nearby cars and cars in front of them that were perceived to most likely to pose a hazard and that they focused less attention on cars in the blind spot or in peripheral vision (*Gugerty 1997; Falzetta 2004; Crundall et al. 1999*). Also it demands greater working memory load to track an object in the blind spot (*Gugerty 1997*).

- Motorists' Level 1 SA of the surrounding traffic significantly degraded when oncoming vehicles were present and the bicyclist was approaching from behind (p-value = 0.025). This observation could be explained by the cue utilization study, which evaluated the extent to which participants' behavior is constrained by environmental cues (*Brunswick 1956; Hursch et al. 1964*). In this experimental scenario, motorists' focal hazard-perception tasks competed for limited cognitive resources and eventually decreased the frequency of detecting peripheral visual events, i.e. the bicyclist approaching from behind led to poor Level 1 SA – a finding consistent with that of Crundall et al. (*Crundall et al. 1999*). However, motorists' projection (Level 3 SA) of the driving environment significantly degraded when the bicyclist was riding ahead of the motorist and oncoming vehicles were present (p-value < 0.001). This can be explained by the limitation of motorists' attentional capacity. With excessive demands on attention due to multiple environmental stimuli, (e.g., presence of a bicycle and oncoming cars), motorists' task performance declined as evidenced by reduced SA.

- Since perception and detection of the hazard is an important criterion of crash avoidance, a Point biserial correlation analysis was conducted between participant's Level 1 SA score and crash occurrence, to determine the relationship between the two factors. A *significant negative linear association was found between the* Level 1 SA score *and crash occurrence (*r_{pbi}*= -0.3, p-value=0.043), indicating that* a *motorist with lower* Level 1 SA scores was more likely to be involved in a crash. *This finding suggests that a common cause of observed crashes was failure to detect the presence of an adjacent bicyclist before turning right during the latter portion of green phase at intersections.*

15.3.3 **Crash Avoidance**

The objective of considering this safety surrogate was to assess if motorists could avoid a crash with the adjacent bicyclist while performing a right-turn during the latter portion of the green phase. Motorist crash avoidance was measured as the number of motorists who could not avoid crashes with a through-moving bicyclist while turning right at 21 simulated signalized intersections. Findings related to crash avoidance are listed below.

- Among 51 participants completing total of 1,071 right-turns, 23 participants could not avoid a crash with a bicyclist in 26 total right-hook crash scenarios. Relative position of a bicyclist, bicyclist speed, and the presence of an oncoming vehicle were found to have a statistically significant effect on crash occurrence. Twenty-four crashes occurred with the bicyclist approaching from behind in the motorists' blind spot and 21 of those crashes occurred in the presence of oncoming left-turning traffic. Additionally, in 23 observed crashes, bicyclists were approaching the intersection at higher speed, i.e. at 16 mph.

- Male participants were involved in more right-hook crashes than female participants (p-value=0.02). Motorists' inadequate surveillance was found to be the major cause of observed right-hook crashes, in most cases (66%), the motorist did not check for the bicyclist in the mirror before turning and, in some cases (15%), they "looked but did not see" (inattention blindness). Some right-hook crashes (19%) were due to motorists' poor projection (the conflicting bicyclist was detected, but the motorist did not yield the right-of-way). This finding *suggests that a common cause of the observed crashes was due to the failure of detecting the adjacent bicyclist.* Near-crash events, where a collision between the right-turning motorist and through-moving bicyclist was imminent if their trajectories remained unchanged, were also investigated. The near-crash events were measured using a TTC upper threshold value of 1.5 seconds. Among 51 participants, who completed a total of 408 right-turns, 20 were involved in 26 severe near-crash events having TTC value less than or equal to 1.5 seconds. Inadequate surveillance was found to be the most common cause of near-crash incidents.

15.4 FIELD VALIDATION

The selection of a location was critical to performing a field validation of the controlled scenarios of bicycle-vehicle interactions found in the driving simulator experiment. After careful search and screening, a location that had similar geometry, significant through bicycles, and right turning vehicle traffic was selected. The research team reviewed 144 hours of video and identified 43 conflicts where the post encroachment time measured less than 5 seconds. The identification of conflicts that exactly matched the simulator was challenged by the relatively small numbers of observations per hour of collected field data, variable bicyclist speeds, and variable volumes of oncoming left-turning vehicular traffic. However, when field observations of scenarios most similar to those in the simulator were isolated, results indicated that the distribution of the PET/TTCs values observed in the simulator were consistent with those observed in the field. It can be concluded that the driving simulator scenarios, for which field data could be collected, modeled authentic driving conditions and that the driver interactions with adjacent bicyclists were representative of real world driver behaviors.

15.5 EFFECT OF DESIGN TREATMENTS

The culminating experiment for this research was to study the effect of design treatments, (specifically signage, pavement markings, curb radii, and protected intersections), on the motorist behavior, using three different motorist performance measures: i) visual attention of motorists, ii) their crash avoidance behavior, and iii) the potential severity of the near collisions or crashes, 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 under the highest driver loading scenario identified in Experiment 1. Additionally, follow-up survey responses were used to evaluate driver comprehension and driver preferences of specific treatments. This section summarizes the findings from each of the four design treatments of the second driving simulator experiment. These results are not found to be statistically significant, unless stated otherwise. However, the lack of a statistically significant effect for a particular treatment does not necessarily mean that the treatment will not have a positive effect on safety, rather that differences in the performance metric being analyzed were not statistically different in the data being analyzed. Finally, although we can measure the various driver performance metrics robustly, it is not yet clear how the magnitudes of the differences can be mapped to expected crash outcomes.

15.5.1 **Sign Treatment**

The findings of Experiment 2 indicate that the level one signage treatment, the ODOT OR10-15b "Turning Vehicles Yield to Bicycles" symbol sign, shown in Figure 15.1, appeared to be an effective method of positively influencing driver behavior, with respect to visual attention.

Figure 15.1: Experimental level one: ODOT OR10-15b "Turning Vehicles Yield to Bicycles"

The conclusions regarding this treatment can be summarized as follows:

- There is a generally positive pattern of change in visual attention with the addition of the sign (level one treatment). The level one signage treatment showed a 4% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero signage treatment. It specifically increased the amount of time spent scanning the side mirror for the bicyclist by 9% and the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 10%, in comparison to the level zero signage treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the sign (level one treatment). The level one signage treatment showed a 7% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero signage treatment. However, the level one signage treatment showed a 3% higher cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero signage treatment

- There is no consistent pattern of change in potential crash severity with the addition of the sign (level one treatment). The level one signage treatment showed a small 3% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero signage treatment. However, the level one signage treatment also showed a 35% larger range of vehicle velocities, in comparison to the level zero signage treatment.

15.5.2 **Pavement Marking Treatment**

The pavement marking treatments include four levels of treatment and a zero level of treatment, all shown in Figure 15.2. The conclusions regarding these treatments can be summarized as follows:

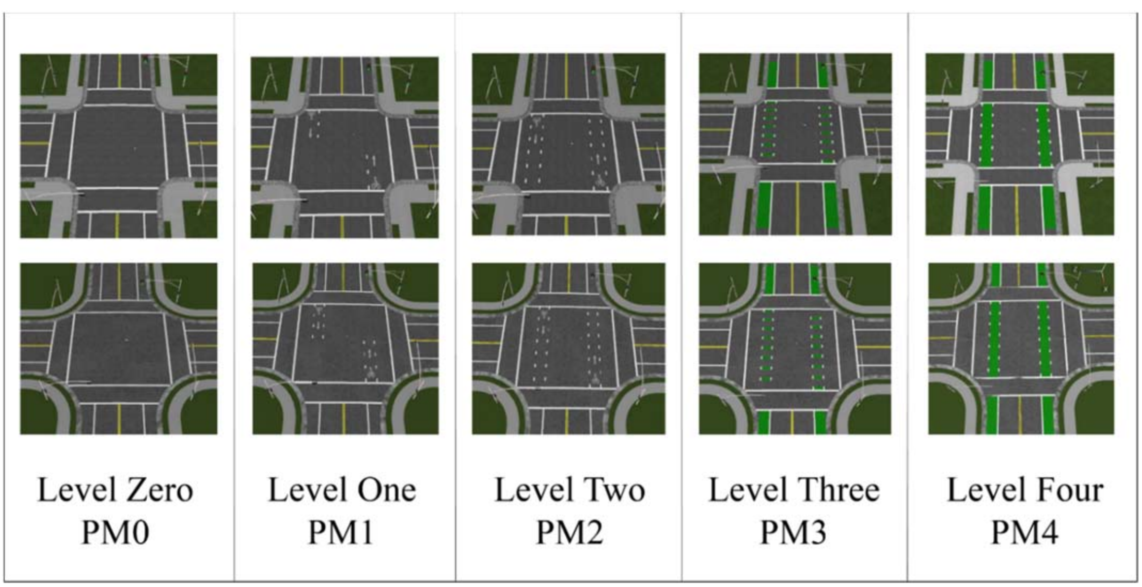


Figure 15.2: Experimental levels of the pavement marking treatment

The findings of Experiment 2 indicate that the level one pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to crash avoidance.

- There is no consistent pattern of change in visual attention with the addition of the dotted white bike line with stencil, single line (level one treatment). The level one pavement marking treatment showed a 1% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment. It specifically increased the amount of time spent scanning the rear mirror by 13% and the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 13%, in comparison to the level zero pavement marking treatment. However, the presence of the level one pavement marking treatment also decreased the amount of time spent scanning the side mirror by 11% and the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 8%, in comparison to the level zero pavement marking treatment.

- There is a generally positive pattern of change in crash avoidance with the addition of the dotted white bike line with stencil, single line (level one treatment). The level one pavement marking treatment showed an 18% increase lower cumulative frequency of high risk TTCs, (equal to or less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Of the five pavement marking treatment levels, the presence of the level one pavement marking tied with the level three pavement marking treatment for the largest decrease in cumulative frequency of high-risk TTC values, in comparison to the level zero pavement marking treatment. Also, the level one pavement marking treatment showed a 15% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

- There is no consistent pattern of change in potential crash severity with the addition of the dotted white bike line with stencil, single line (level one treatment). The level one pavement marking treatment showed a 6% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. However, the level one pavement marking treatment also showed a 36% smaller range of vehicle velocities, in comparison to the level zero pavement marking treatment.

The findings of Experiment 2 indicate that the level two pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to visual attention.

- There is a generally positive pattern of change in visual attention with the addition of the dotted white bike line with stencil, double line (level two treatment). The presence of the level two pavement marking treatment showed a 10% increase in motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment (it is tied with the level four pavement marking treatment for the highest rate for all five pavement marking treatment levels). It also specifically increased the amount of time motorists' spent scanning the side mirror in close proximity to the intersection (when the bicyclist is visible within the side mirror) by 13%, in comparison to the level zero pavement marking treatment. However, the presence of the level two pavement marking treatment also decreased the amount of time motorists' spent scanning the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 6%, in comparison to the level zero pavement marking treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the dotted white bike line with stencil, double line (level two treatment). The level one pavement marking treatment showed a 12% higher cumulative frequency of high risk TTCs, (equal to or less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Of the five pavement marking treatment levels, the presence of the level two pavement marking treatment had the largest increase in cumulative frequency of high-risk TTC values. However, the level one pavement marking treatment showed a 4% lower cumulative frequency of high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

- There is a generally negative pattern of change in potential crash severity with the addition of the dotted white bike line with stencil, double line (level two treatment). The level two pavement marking treatment showed a 6% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. Additionally, the level two pavement marking treatment also showed a 14% larger range of vehicle velocities, in comparison to the level zero pavement marking treatment.

- It is important to note that the level two pavement marking treatment was the most preferred, according to the follow-up survey responses, with 50% of participants selecting it as their preferred pavement marking treatment.

The findings of Experiment 2 indicate that the level three pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to crash avoidance.

- There is no consistent pattern of change in visual attention with the addition of the skipped green bike lanes with white outline (level three treatment). The presence of the level three pavement marking treatment showed a 9% increase in motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment. It specifically increased the amount of time motorists' spent scanning the rear mirror by 10%, in comparison to the level zero pavement marking treatment. However, the presence of the level three pavement marking treatment also decreased the amount of time motorists' spent scanning the side mirror by 12% and the rear mirror in close proximity to the intersection (when the bicyclist is visible within the rear mirror) by 6%, in comparison to the level zero pavement marking treatment.

- There is a generally positive pattern of change in crash avoidance with the addition of the skipped green bike lanes with white outline (level three treatment). The presence of the level three pavement marking treatment had a statistically significant effect on the distribution of collisions and near-collisions, in comparison to the level zero pavement marking treatment (100% decrease in collisions and 18% decrease in near-collisions, with a p-value = 0.01). Also, the level three pavement marking treatment showed an 18% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero signage treatment. Of the five pavement marking treatment levels, the presence of the level three pavement marking tied with the level one pavement marking treatment for the largest decrease in cumulative frequency of high-risk TTC values, in comparison to the level zero pavement marking treatment. Also, the level three pavement marking showed a 2% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking.

- There is a generally negative pattern of change in potential crash severity with the addition of the skipped green bike lanes with white outline (level three treatment). The level three pavement marking treatment showed a 22% increase in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. The level three pavement marking has the highest mean velocity of all pavement marking treatment levels. Additionally, the level three pavement marking treatment also showed a 1% larger range of vehicle velocities, in comparison to the level zero pavement marking treatment.

The findings of Experiment 2 indicate that the level four pavement marking treatment appears to be an effective method of positively influencing driver behavior with respect to crash avoidance and potential crash severity.

- There is a generally negative pattern of change in visual attention with the addition of the full green bike lanes with dotted white outline (level four treatment). The presence of the level four pavement marking treatment showed a 10% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero pavement marking treatment (it is tied with the level two pavement marking treatment for the highest rate for all five pavement marking treatment levels). However, the level four pavement marking treatment decreased the amount of time spent scanning the rearview and side mirrors in close proximity to the intersection (when the bicyclist is visible) by 12% and 22%, respectively, and the amount of time spent scanning the side mirror on the approach by 4%, in comparison to the level zero pavement marking treatment. The decrease in the amount of time spent scanning the side mirror in close proximity to the intersection was found to be statistically significant (p-value = 0.03).

- There is a generally positive pattern of change in crash avoidance with the addition of the full green bike lanes with dotted white outline (level four treatment). The level four pavement marking treatment showed a 13% lower relative frequency of high-risk TTC values (less than 0.9 seconds), in comparison to the level zero pavement marking treatment. Also, the level four pavement marking treatment showed a 12% lower cumulative frequency of moderate and high risk TTCs, (equal to or less than 1.5 seconds), in comparison to the level zero pavement marking treatment.

- There is a generally positive pattern of change in potential crash severity with the addition of the full green bike lanes with dotted white outline (level four treatment). The level three pavement marking treatment showed a 1% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero pavement marking treatment. Additionally, the level four pavement marking treatment also showed a 38% smaller range of vehicle velocities, in comparison to the level zero pavement marking treatment.

- It is also important to note that when the survey responses for pavement marking treatment preference are broken down by gender, the level four pavement marking treatment was the most preferred by males, with 44% of male participants selecting it as their preferred pavement marking treatment.

15.5.3 Curb Radii Treatment

The findings of Experiment 2 indicate that the smaller, level one curb radii treatment, shown in Figure 15.3, appears to be an effective method of positively influencing driver behavior, with respect to crash avoidance and potential crash severity. The level zero curb radii treatment has 30 ft. curb radii and the level one curb radii treatment has 10 ft. curb radii.

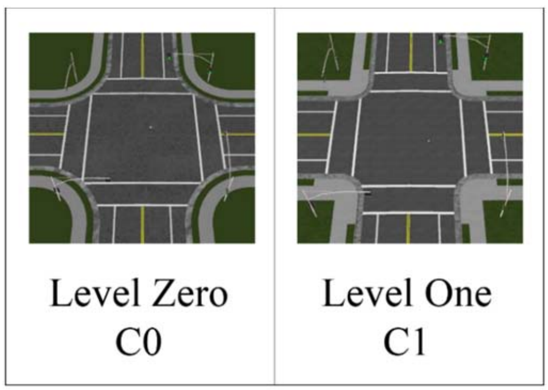


Figure 15.3: Experimental levels of the curb radii treatment

The conclusions regarding these treatments can be summarized as follows:

- There is no consistent pattern of change in visual attention with the addition of the smaller curb radii (level one treatment). The presence of the smaller, level one curb radii treatment showed a 3% lower rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero curb radii treatment. The level one curb radii treatment decreased the amount of time spent scanning the side mirror by 15% and the rear mirror by 17%, in comparison to the level zero curb radii treatment. The decrease in the amount of time spent scanning the side mirror was found to be statistically significant (p-value = 0.04). However, the presence of the smaller, level one curb radii treatment increased the amount of time spent scanning the rearview mirror for the bicyclist in close proximity to the intersection (when the bicyclist is visible) by 14%, in comparison to the level zero curb radii treatment.

- There is a generally positive pattern of change in crash avoidance with the addition of the smaller curb radii (level one treatment). The level one curb radii treatment has the same cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero curb radii treatment. Additionally, the level one curb radii treatment showed a 7% lower cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero curb radii treatment.

- There is a generally positive pattern of change in potential crash severity with the addition of the smaller curb radii (level one treatment). The level one curb radii treatment showed a 4% decrease in the mean vehicle velocity during moderate- to high-risk incidents, in comparison to the level zero curb radii treatment. Additionally, the level one curb radii treatment showed a 54% smaller range of vehicle velocities, in comparison to the level zero curb radii treatment. This finding of lower speeds for the smaller radii is a clear benefit and is consistent with the formulaic relationship between the design speed and the minimum radius of curvature, found in the AASHTO "A Policy on Geometric Design of Highways and Streets" *(AAHSTO 2011).*

15.5.4 **Protected Intersection Treatment**

The protected intersection treatments include two levels of protected intersection treatment and a level zero of protected intersection treatment, all shown in Figure 15.4. It should be noted that the protected intersection design used in the simulator was not intended to study constructability issues such as the truck turning/mountable curbs, reflective markings on curbs for visibility issues at night, and issues about downhill grades and accommodation of pedestrians

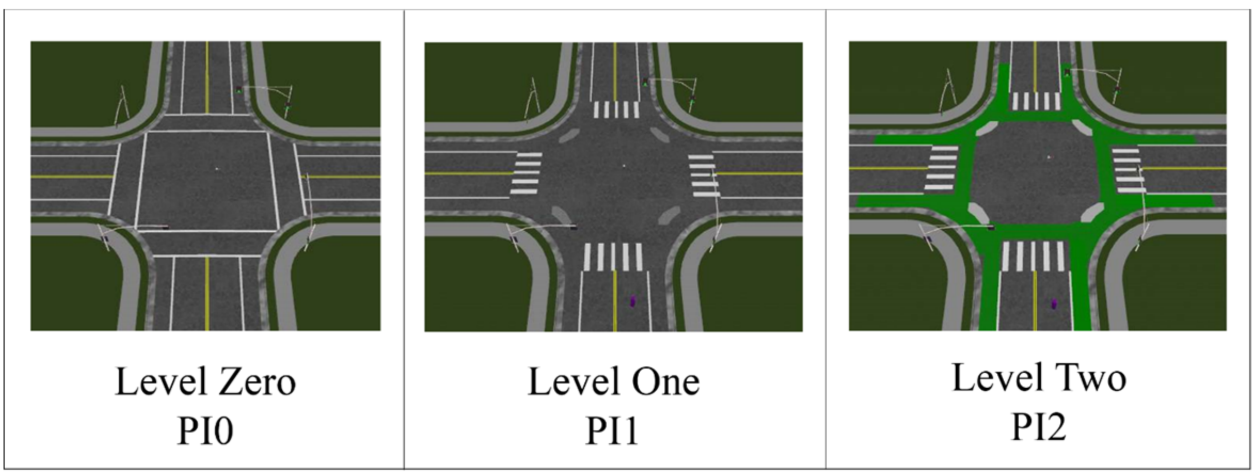


Figure 15.4: Experimental levels of the protected intersection treatment

The conclusions regarding these treatments can be summarized as follows:

The findings of Experiment 2 indicate that the level one protected intersection treatments appears to be an effective method of positively influencing driver behavior with respect to potential crash severity.

- There is a generally negative pattern of change in visual attention with the addition of the protected intersection with islands (level one treatment). The presence of the level one protected intersection treatment showed a 3% lower rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero protected intersection treatment. It decreased the amount of time spend scanning the rear mirror by 19%, the side mirror by 24%, and the side mirror in close proximity to the intersection (when the bicyclist is visible in the side mirror) by 75%, in comparison to the level zero protected intersection treatment. However, it also increased the amount of time spent scanning the rear mirror for the bicyclist in close proximity to the intersection (when the bicyclist is visible in the rear mirror) by 7%, in comparison to the level zero protected intersection treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the protected intersection with islands (level one treatment). The level one protected intersection treatment showed a 19% lower cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero protected intersection treatment. Additionally, the level one protected intersection treatment showed a 5% higher cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero protected intersection treatment.

- There is a generally positive pattern of change in potential crash severity with the addition of the protected intersection with islands (level one treatment). The level one protected intersection treatment showed a 15% decrease in the mean velocity during moderate- to high-risk incidents, in comparison to the level zero protected intersection treatment. The impact of the level one protected intersection treatment on the range of vehicle velocities was unable to be calculated.

The findings of Experiment 2 indicate that the level two protected intersection treatment does not appear to be a consistently effective method of positively influencing driver behavior.

- There is no consistent pattern of change in visual attention with the addition of the protected intersection with islands and green pavement markings (level two treatment). The presence of the level two protected intersection treatment showed a 6% higher rate of motorist fixations on the bicyclist-related AOIs, in comparison to the level zero protected intersection treatment. It specifically increased the amount of time spent scanning the rear mirror for the bicyclist by 42%, in comparison to the level zero protected intersection treatment. However, it decreased the amount of time spent scanning the side mirror by 52%, and the rear and side mirror in close proximity to the intersection (when the bicyclist is visible in the mirror) by 55% and 25%, respectively, in comparison to the level zero protected intersection treatment.

- There is no consistent pattern of change in crash avoidance with the addition of the protected intersection with islands and green pavement markings (level two treatment). The level two protected intersection treatment showed a 15% lower cumulative frequency of high risk TTC values, (equal to or less than 0.9 seconds), in comparison to the level zero protected intersection treatment. Additionally, the level two protected intersection treatment showed a 13% higher cumulative frequency of moderate and high risk TTC values, (equal to or less than 1.5 seconds), in comparison to the level zero protected intersection treatment. Also, the frequencies of both the moderate risk TTCs and high-risk TTCs were significantly lower than the level one protected intersection treatment (19 vs. 5 and 15 vs. 3, respectively).

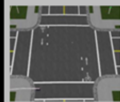
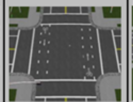
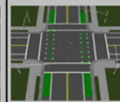
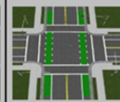
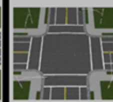
- There is no consistent pattern of change in potential crash severity with the addition of the protected intersection with islands and green pavement markings (level two treatment). The level two protected intersection treatment showed a 10% decrease in the mean velocity during moderate- to high-risk incidents, in comparison to the level zero protected intersection treatment. However, the level two protected intersection treatment showed a 55% larger range of vehicle velocities, in comparison to the level zero protected intersection treatment.

- It is important to note that the level two protected intersection treatment out-performed the level one protected intersection treatment, with respect to the frequencies of driver comprehension of the correct vehicle path by 3%. The correct vehicle path is defined as the vehicle traveling around the island while executing the right turn and specifically not traveling on the bicyclist path located between the island and the curb.

15.6 SUMMARY

This research produced a very consistent and coherent narrative about the right-hook crash. The research identified the intersection configuration with a bike lane to the right of a though motor vehicle lane as the most common profile. The research proceed to identify the traffic situations that introduced the highest probabilities for driver errors. Then a carefully selected set of treatments were evaluated under these loading scenarios. The robust analysis of these driver performance measurable in the simulator was interpreted based on the positive outcome on various levels of driver performance as it relates to the safety of bicyclist.

Figure 15.6 summarizes the results of Experiment 2 on the three metrics from the driving simulator and the one metric obtained from the survey. For clarification, the survey metric represents two different types of conclusions: for the pavement marking treatment, it represents the surveyed participant preference of the four pavement marking treatment levels, and for the protected intersection, it represents the measured driver comprehension of the correct vehicle path, (which is presented in Chapter 14, “Results: Experiment 2 Survey”). Blue checks indicate that the treatment had an improvement for the performance measure, the red Xs indicates that the treatment had a negative change for the performance measure, and the white dashes indicate no consistent pattern of improvement. It is notable that all treatments had some positive effect on measured driver performance. The sign, pavement markings and curb radius treatment groups are not mutually exclusive (i.e. the sign, a pavement marking, and smaller curb radius could be applied together).

Performance Measures	S1 	PM1 	PM2 	PM3 	PM4 	C1 	PI1 	PI2 
Visual Attention	✓	—	✓	—	✗	—	✗	—
Crash Avoidance	—	✓	—	✓	✓	✓	—	—
Potential Crash Severity	—	—	✗	✗	✓	✓	✓	—
Survey	n/a		✓ *			n/a	✗ **	✓ **

**This conclusion relates to the participants' selected preference of PM2 over the other three pavement marking treatment levels within the follow-up survey.*
***These conclusions relate to the measured driver comprehension of the correct vehicle path, which is presented in Chapter 14 "Results: Experiment 2 Survey.".*

Figure 15.5: Summary of Experiment 2 treatment performance

In summary, the following observations and recommendations about each of the four treatment categories are:

- The presence of the sign improved driver performance across the visual attention spectrum. It appears the sign attracted driver's attentions and resulted in more searching for people on bicycles. Thus, given the relatively low cost of the sign, the "Turning Vehicles Yield to Bicycles" sign should be installed where feasible. To maximize the impacts, the sign should be installed in a location most visible to drivers and in advance of the turning-merge conflict area.

- The presence of through intersection markings also improved measured driver performance in the searching and crash avoidance spectrums. While all tested designs had some positive effects, the evidence from the simulator suggests that either the single, dotted white bike line with bicycle stencil pavement marking or the double, dotted white bike line with bicycle stencil pavement marking should be considered. The addition of green markings, commonly associated with bicycles, did not change the driver's visual attention measures as much as the simpler dotted line markings. The solid green marking, in fact, saw decreased visual attention performance.

- The use of a smaller curb radii produced decreases in vehicle turning speed and lower numbers of the high-risk conflicts. The reduction in vehicle turning speed was expected but is a clear measured benefit for safety.

- While the other treatments are easily implementable, the protected intersections with an island and/or green pavement marking would require further design work and consideration of many issues that were 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 corresponds to the curb radii treatments as the radii is larger for both treatments. The protected intersection design moves the conflict point between the car and bicycle forward in the intersection so it is different than the other treatments in that respect. Finally, unlike the other treatments, this was a novel design and not familiar to any driver.

15.7 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. While we can measure the various driver performance metrics robustly, it is not yet clear how to map the magnitudes of the differences to expected crash outcomes. Additional work is recommended to address the limitations of this study and to further consider the potential effects of the right-hook crash mitigation strategies from this research.

- One of the fundamental limitations of within-subject design is fatigue effects that can cause participant's performance to decline over time during the experiment. There is the possibility that participants might get tired or bored as the experiment progressed. Also, repeated right-turning maneuvers pose the threat of inducing simulator sickness more frequently than through movements in simulated driving. Therefore, to reduce the risk of fatigue effect and simulator sickness, the experiment could be conducted in two trials on two different days.

- Although many studies found an effect of driving experience on motorist's visual attention in driving simulator experiments *(Underwood et al. 2003; Pradhan et al. 2005),* this study did not find any significant difference on motorist's performance with respect to driving experience. A larger and more diverse sample may indicate some significance of driving experience on motorist's visual attention and crash avoidance.

- Additional variables could be included in the experiment to determine their effects on the occurrence of right-hook crashes, for example the conspicuity of bicyclist, and time of day. The assumption of constant speed of the approaching bicyclist is limiting; in reality some people on bicycles would slow down to avoid a collision or near collision.

- As noted, there are differences in Oregon driving code and practices with striping bicycle lanes all the way to the intersection that differs from practices in other states. Thus the use of drivers living in Oregon are likely to reflect the training and understanding of these designs that might differ from drivers elsewhere.

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APPENDIX A:

GLOSSARY

APPENDIX A: Glossary

This appendix contains the definition of abbreviations and acronyms, as well as the definitions of common terms.

Table A-1: Abbreviations and acronym definitions

Acronym/Abbreviation	Definition
ASL	Applied Science Laboratories
AOI	Area of Interest
ANOVA	Analysis of Variance
ATFD	Average Total Fixation Duration
BMV	Bicycle-Motor Vehicle
C	Curb radii Treatment
CHAR	Center for Healthy Aging Research
CIs	Confidence Intervals
FHWA	Federal Highway Administration
HSD	Honest Significant Difference
IRB	Institutional Review Board
ISA	Internet Scene Assembler
ITE	Institute of Transportation Engineers
ITTE	Institute of Transportation and Traffic Engineering
LCD	Liquid-Crystal Display
MANOVA	Multiple Analysis of Variance
MAT	Manual Accident Typing
mph	Miles per Hour
NC	Near-Collision
NCHS	National Center for Health Statistics
NEISS	National Electronic Injury Surveillance System
NHTS	National Household Travel Surveys
NHTSA	National Highway Traffic Safety Administration
NMVCCS	National Motor Vehicle Crash Causation Survey
NPTS	National Personal Transportation Surveys
ODOT	Oregon Department of Transportation
OSU	Oregon State University
PBCAT	Pedestrian and Bicycle Crash Analysis Tool
PI	Protected Intersection Treatment
PM	Pavement Marking Treatment
PET	Post-Encroachment Time

Acronym/Abbreviation	Definition
ROC	Risk of Collision
RQ	Research Question
RV	Rearview
S	Signage Treatment
SA	Situational Awareness
SAE	Society of Automotive Engineers
SAGAT	Situational Awareness Global Assessment Technique
SART	Situational Awareness Rating Technique
SPAM	Situational Present Awareness Method
SSAM	Surrogate Safety Assessment Model
SUV	Sport Utility Vehicle
TTC	Time-to-Collision
TTC_{min}	Minimum Time-to-Collision
UFOV	Useful Field of View

Table A-2. Definitions of common terminology in the report

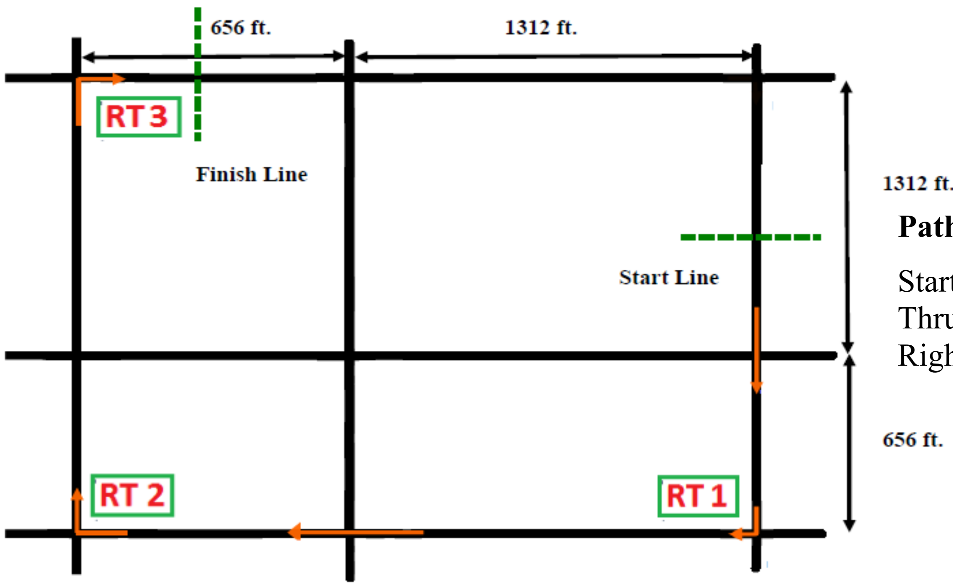
Term	Definition
Area of Interest	An area within the motorist field of view that is identified as potentially influential to the results of the visual attention analysis.
(Standard) Bike Lane	 A standard bike lane usually consists of a four to six foot lane, separated from traffic lanes by a six- to eight-inch white line. They may be either curb-tight (left) or adjacent to a parking strip (right). 
Crash Avoidance	Crash avoidance is a global performance measure that helped to determine if a motorist was able to notice a bicyclist in a timely manner, decide to avoid the collision, and execute an evasive maneuver to ultimately avoid a right-hook crash at a simulated signalized intersection.
Cumulative Frequency	In this case, cumulative frequency represents the percentage of incidents with TTC values that fall below either 0.9 sec or 1.5 sec, (as specified), out of the total number of incidents that occurred for the specific treatment level.
Near-Collision	Scenario where two road users pass in close proximity to one another, but a collision does not take place.
Post-Encroachment Time	The time between the first road user leaving the common spatial zone and the second arriving at it. Abbreviated as PET.
Potential Crash Severity	Potential crash severityis a performance measure that utilized motor vehicle velocities at the time of a collision or near-collision to determine the severity of resulting collisions that occurred or would have occurred. Higher velocities at the time of collision are associated with more severe injuries.
Protected Intersection	A protected intersection is a type of intersection, with specific geometric designs that provide positive separation between the motorist and bicyclist paths within the functional area of the intersection. In this case, the positive separation was produced with the use of raised islands.
Right-hook crash	Right-hook crashes describe a type of bicycle-motor vehicle crash that occurs between a right-turning vehicle and a through-moving bicycle at an intersection.
Risk of Collision Score	Risk of Collision is "a subjective measure of the seriousness of the observed conflict and is dependent on the perceived control that the driver has over the conflict situation, the severity of the evasive maneuver and the presence of other road users or constricting factors which limit the driver's response options" *(Sayed et al. 1999).* Abbreviated as ROC.
Situational Awareness	Situational awareness is "the updated, meaningful knowledge of an unpredictably-changing, multifaceted situation that operators use to guide choice and action when engaged in real-time multitasking," including motorist route location, location of nearby traffic and pedestrians, fuel levels, and so on *(Gugerty 2011).* Abbreviated as SA.
(Level 1) Situation Awareness	Level 1 situational awareness involves the perception of elements within the environment. Abbreviated as Level 1 SA.

Term	Definition
(Level 2) Situation Awareness	Level 2 situational awareness comprehension of the current situation by integrating various pieces of data and information collected in Level 1 SA in conjunction with operator goals. Abbreviated as Level 2 SA.
(Level 3) Situation Awareness	Level 1 situational awareness involves the projection of future status from the knowledge of the elements and comprehension of the situation achieved in Level 1 and Level 2 SA. Level 3 SA allows the motorist to perform timely and effective decision making. Abbreviated as Level 3 SA.
Through bike lane	A marked bike lane that suggests where bicyclists should ride that is used in the turning zone designs. These bike lanes makings are skipped rather than solid meaning motor vehicles may use these lanes when no bicycles are present.
Time-to-Collision	Time-to-Collision is a commonly used severity indicator of traffic conflicts and near misses is the Time-to-Collision (TTC), which is defined as "the time required for two vehicles to collide if they continue at their present speeds and on the same path" *(Hayward 1972; Hydén 1987).*Abbreviated as TTC.
(Minimum) Time-to-Collision	The minimum Time-to-Collision is represented by the minimum TTC value (TTCmin), which is defined as "the minimum time distance between two vehicles during the collision avoidance process" *(van der Horst 1984).*
Visual Attention	Visual attention of motorists is a performance measure that was measured using eye-movement data collected with eye-tracker technology.

APPENDIX B

EXPERIMENT 1 GRID LAYOUTS

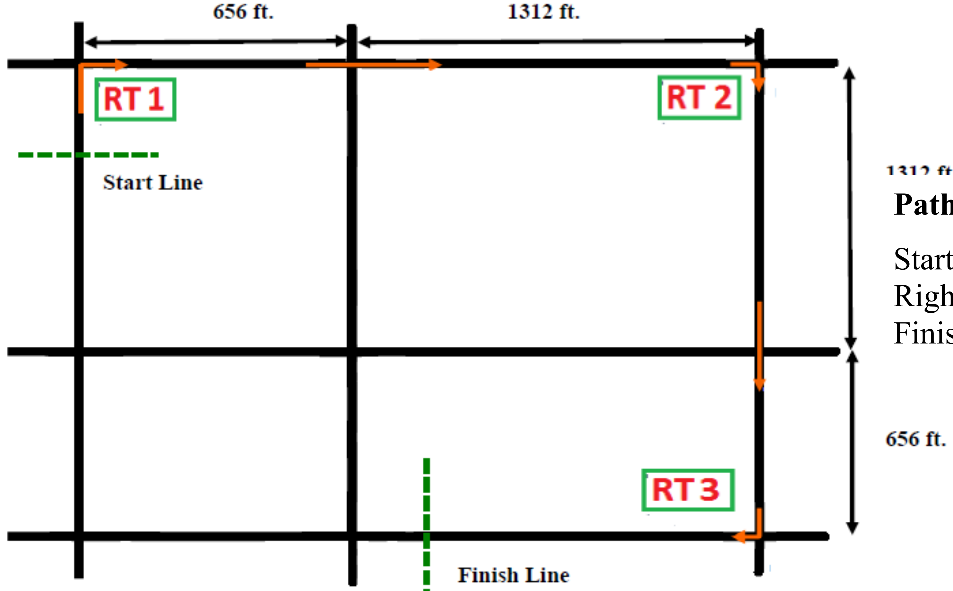
APPENDIX B: Experiment 1 grid layouts



Path:

Start-Thru-Right-Thru-Right-Thru-Right-Finish

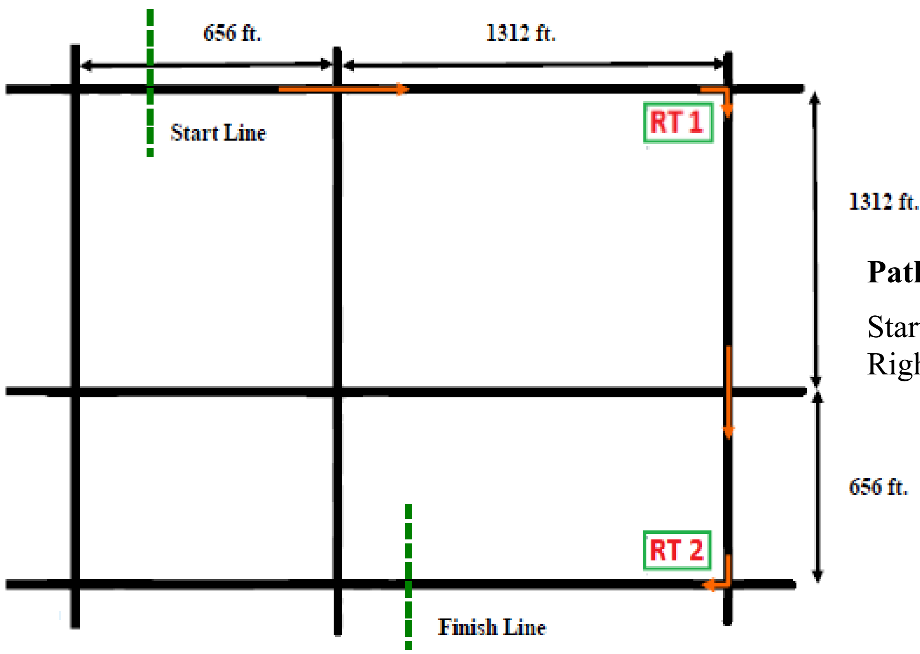
Layout A3-Grid 6



Path:

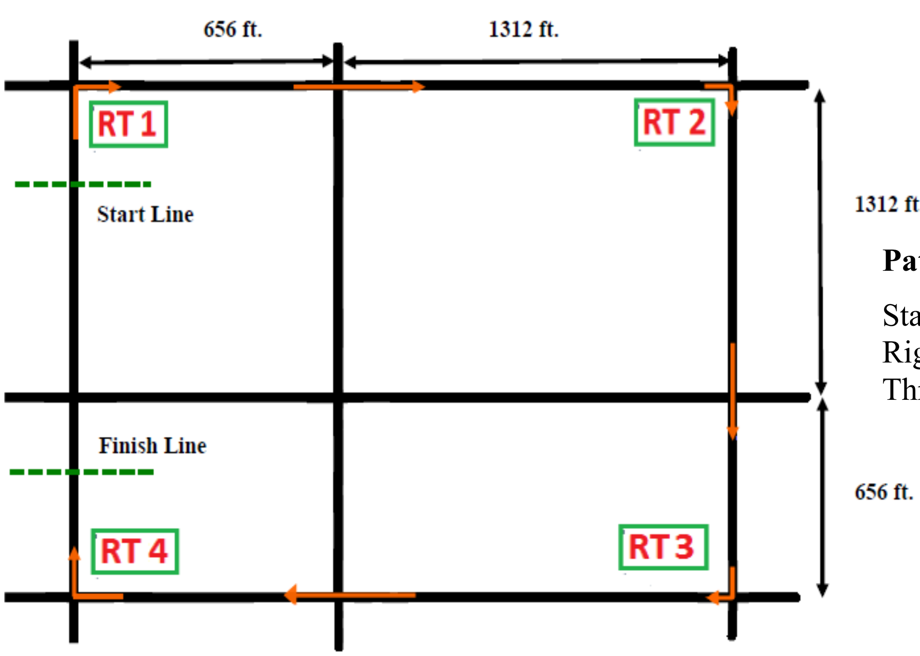
Start-Right-Thru-Right-Thru-Right-Finish

Layout A2-Grid 4



Path:

Start-Thru-Right-Thru-Right-Finish



Path:

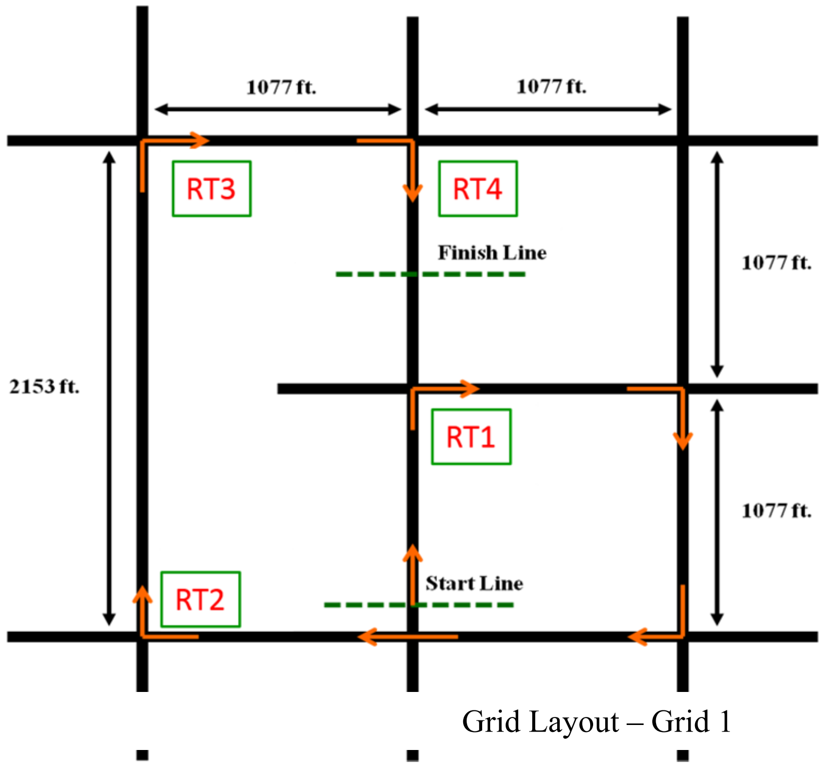
Start-Right-Thru-Right-Thru-Right-Thru-Right-Finish

Figure: Grid layout of (a) two right-turning intersections – grid 5 and (b) four right-turning intersections – grid 3

APPENDIX C

EXPERIMENT 2 GRID LAYOUTS

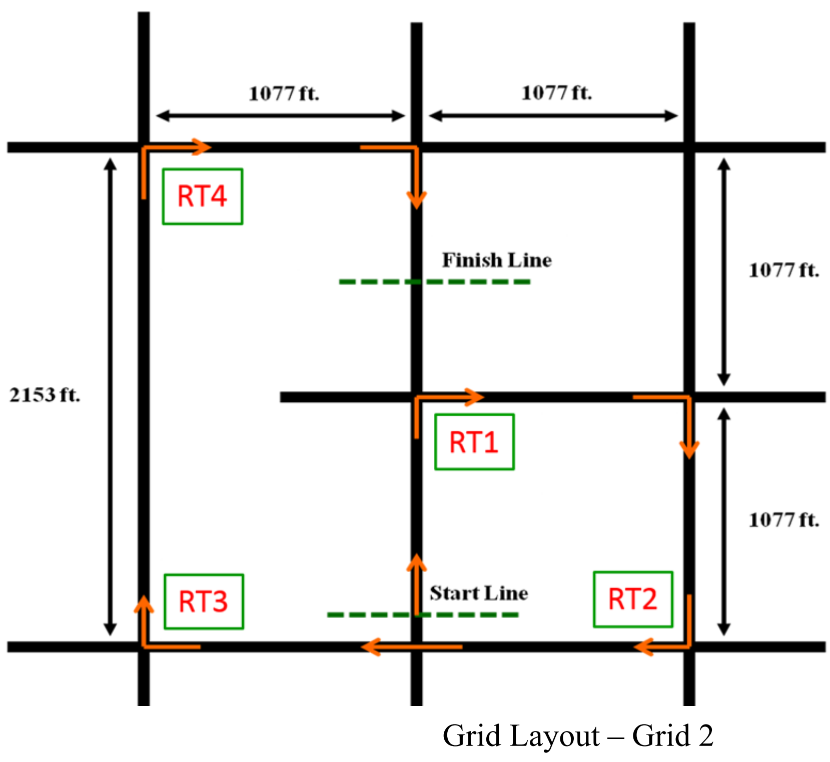
APPENDIX C: Experiment 2 Grid Layouts



Grid Layout – Grid 1

Path:

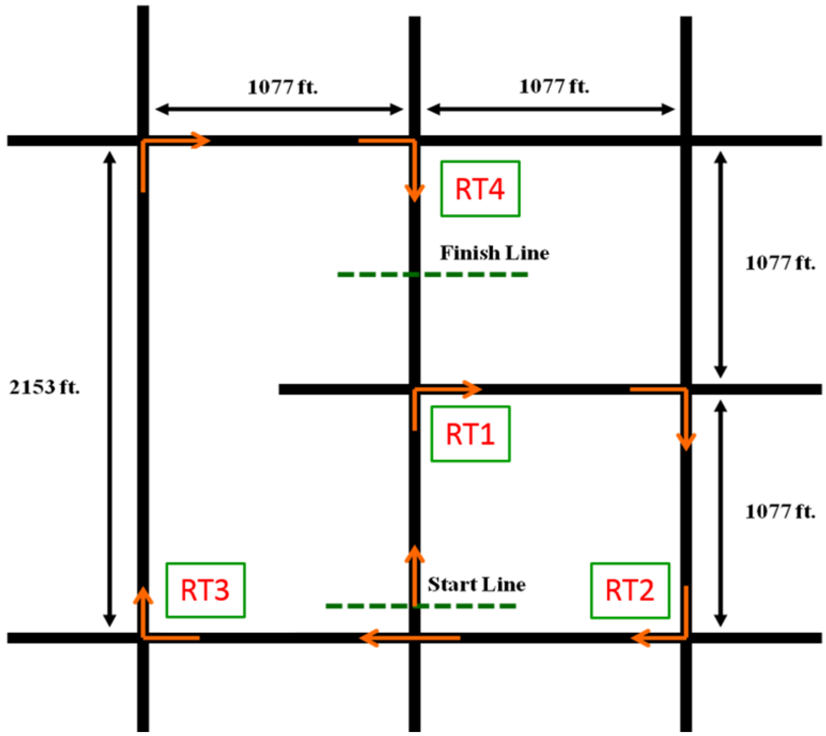
Start-Right- Right-Right-Thru-Right-Right-Right-Finish



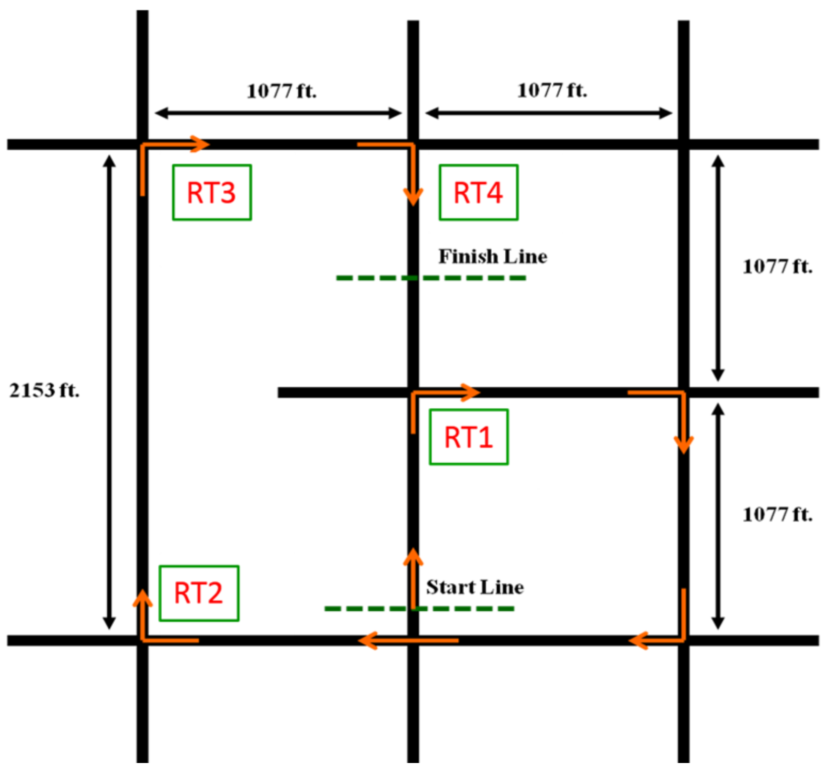
Grid Layout – Grid 2

Path:

Start-Right- Right-Right-Thru-Right-Right-Right-Finish

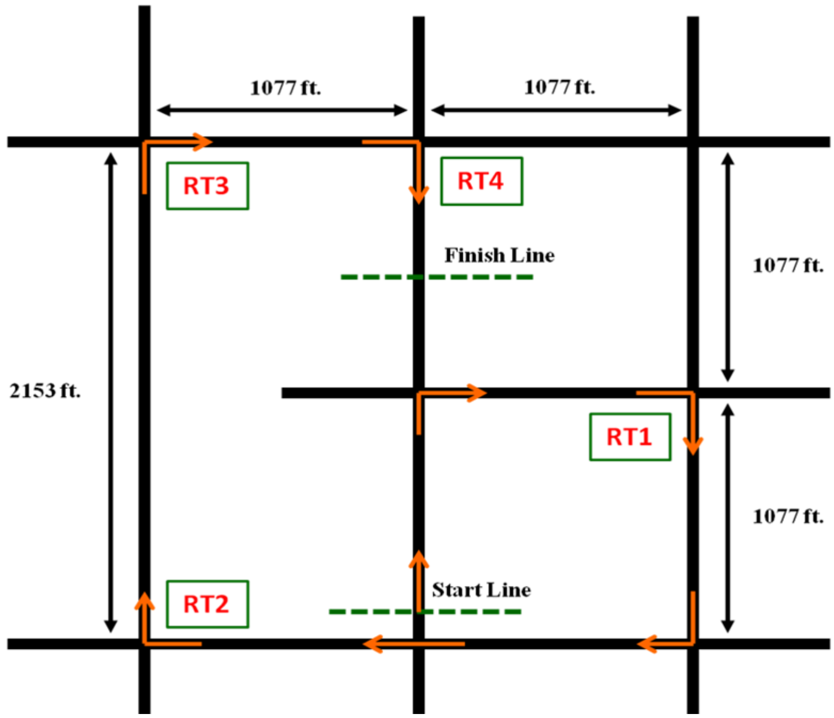


Grid Layout – Grid 3

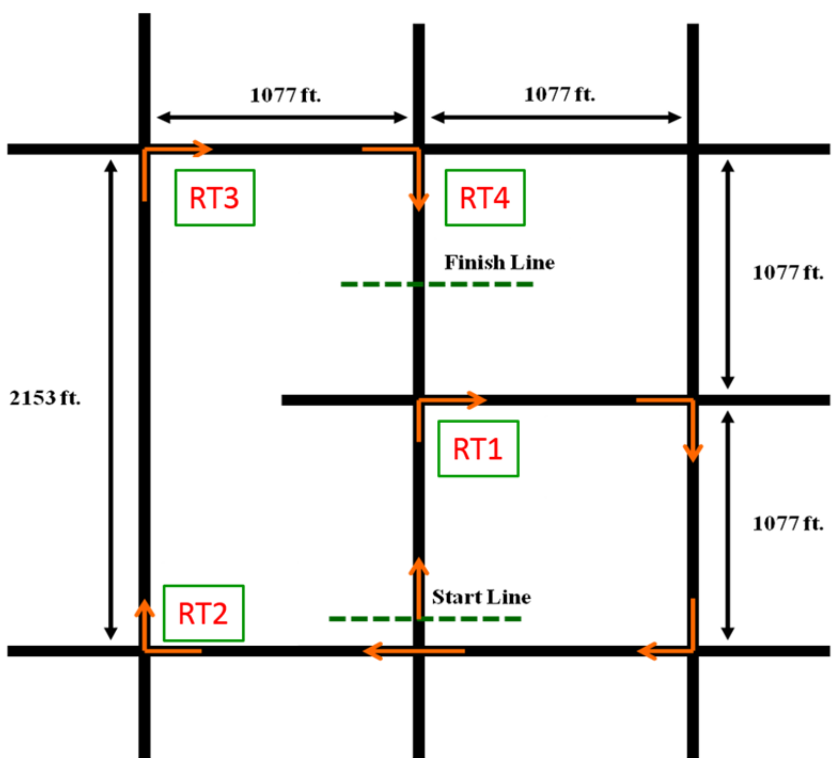


Grid Layout – Grid 4

Path:



Grid Layout – Grid 5



Grid Layout – Grid 6

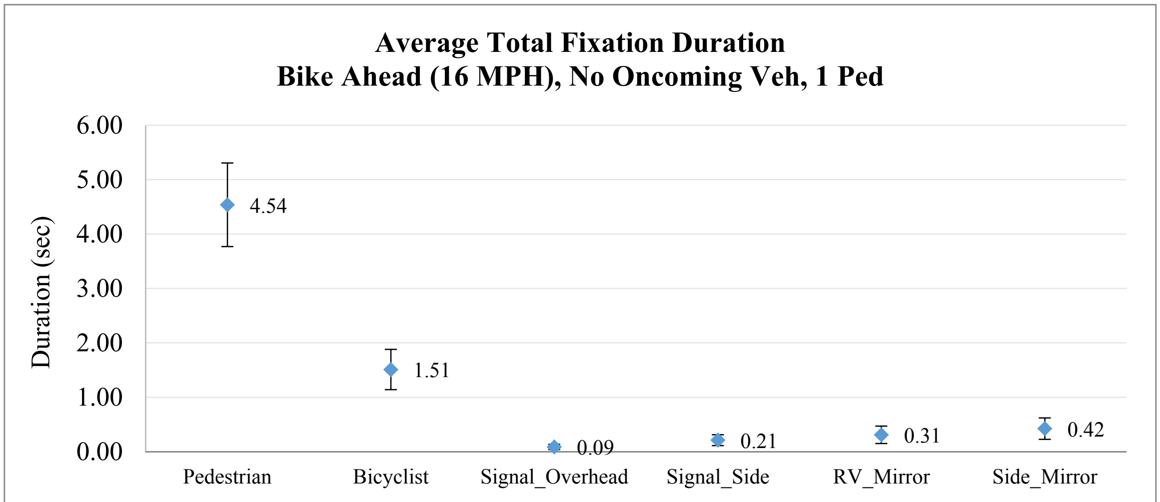
Path:

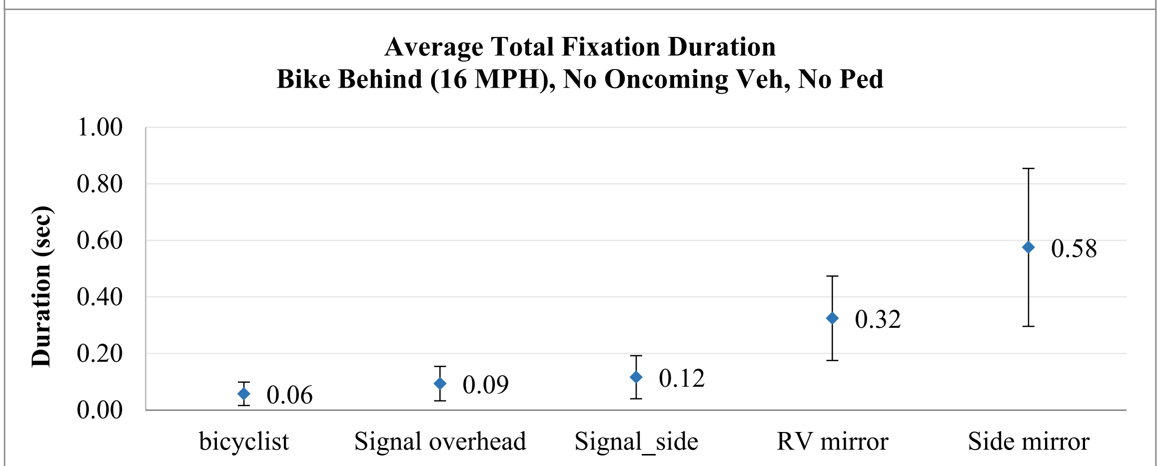
Start-Right- Right-Right-Thru-Right-Right-Right-Finish

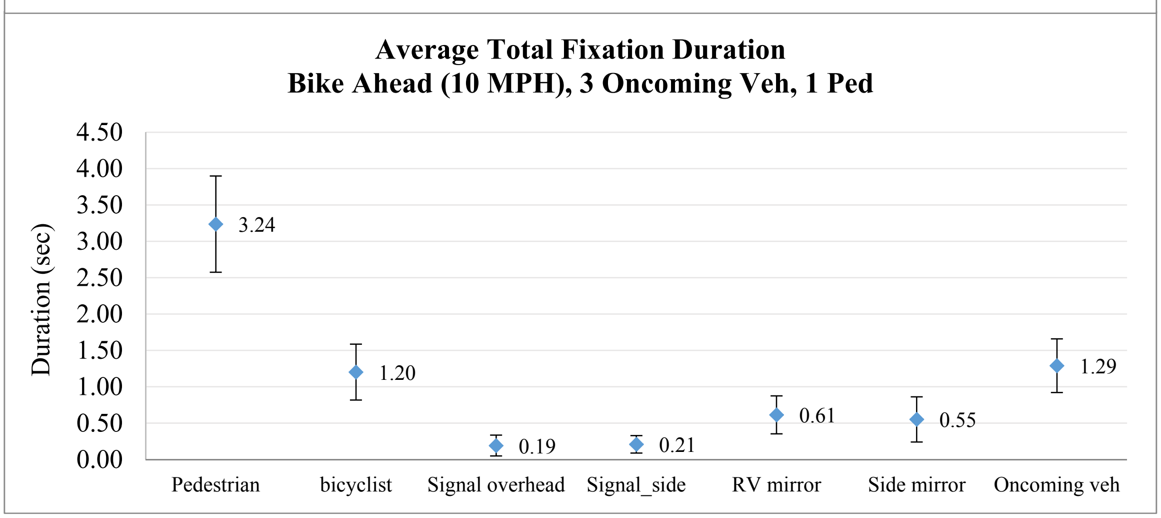
APPENDIX D

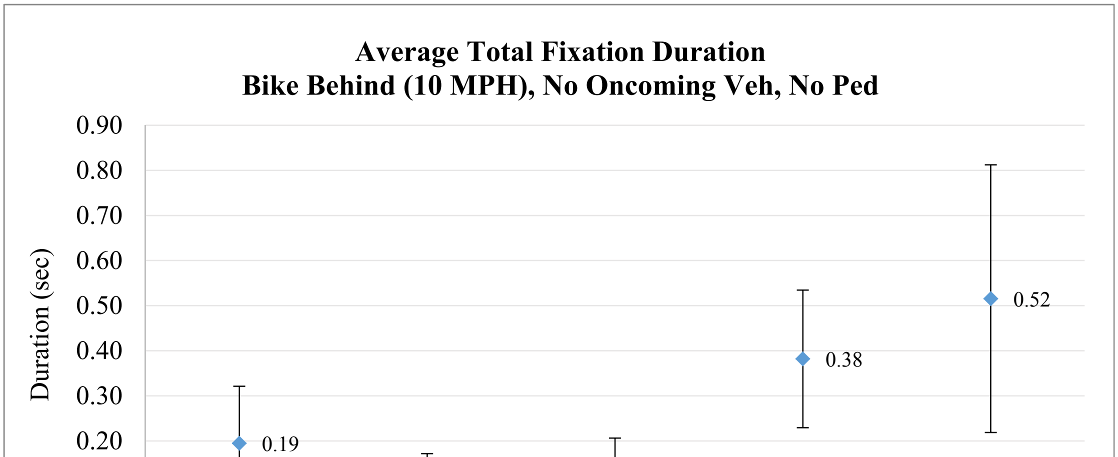
AVERAGE TOTAL FIXATION DURATION (ATFD) WITH 95% CI FOR ALL INTERSECTIONS

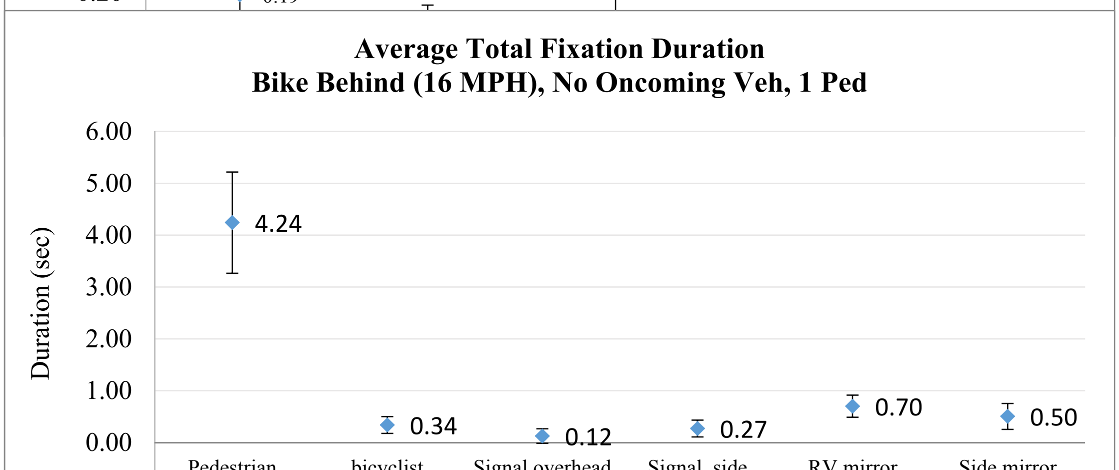
APPENDIX D: Average Total Fixation Duration (ATFD) with 95% CI for all Intersections

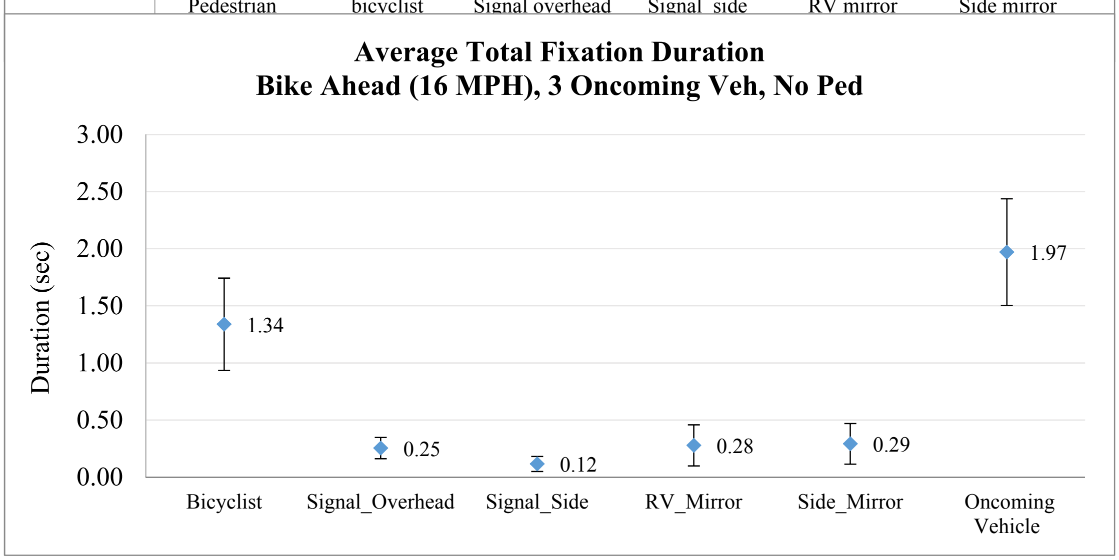


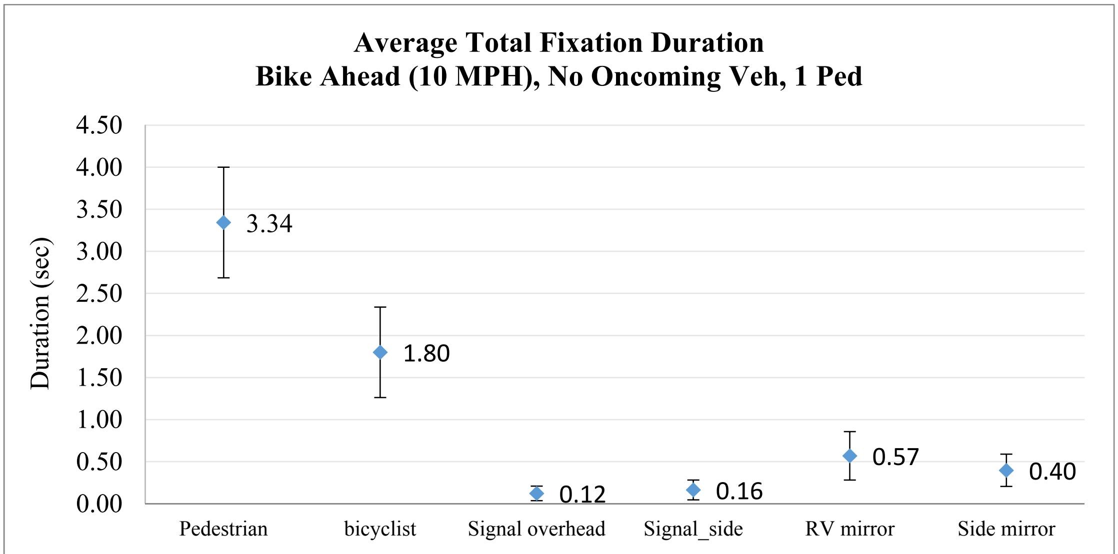


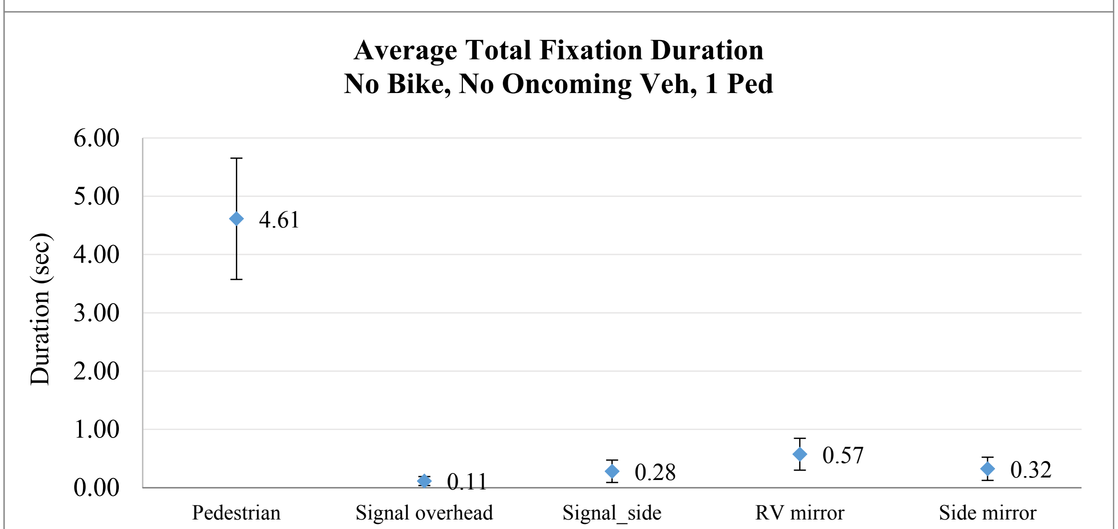


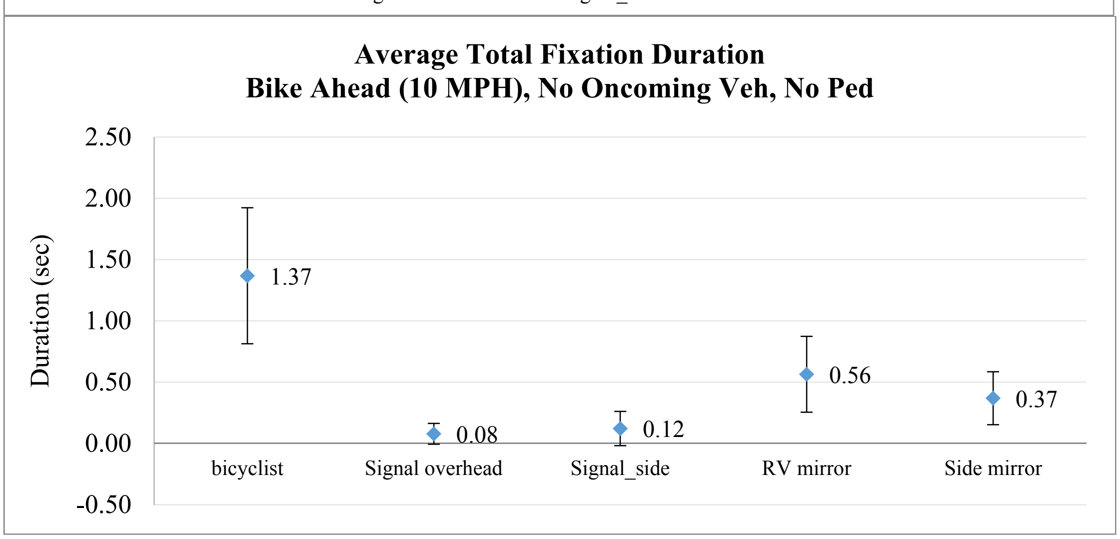

Average Total Fixation Duration
Bike Behind (10 MPH), No Oncoming Veh, No Ped
Duration (sec)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.19
0.38
0.52

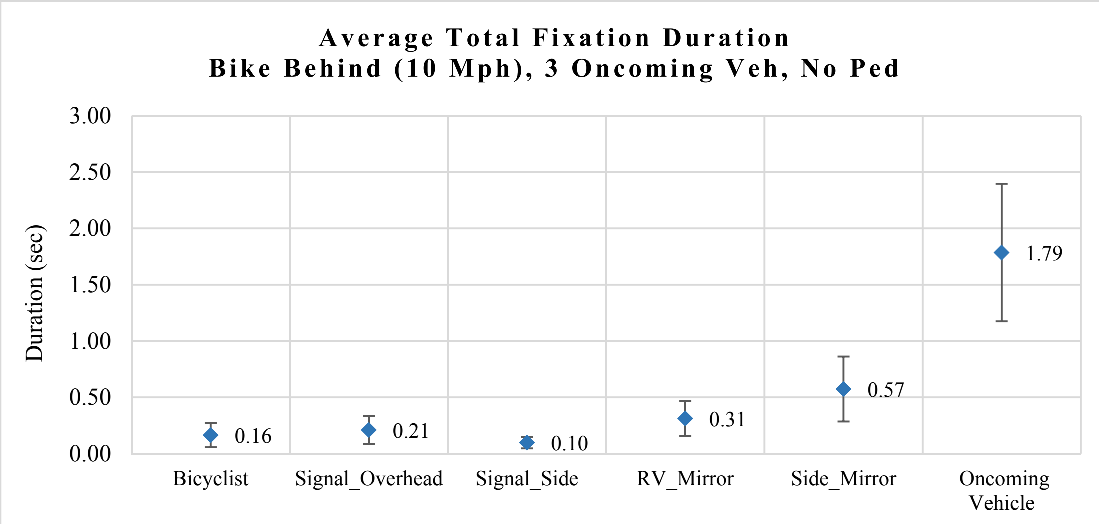

Average Total Fixation Duration
Bike Behind (16 MPH), No Oncoming Veh, 1 Ped
Duration (sec)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4.24
0.34
0.12
0.27
0.70
0.50
Pedestrian
bicyclist
Signal overhead
Signal side
RV mirror
Side mirror

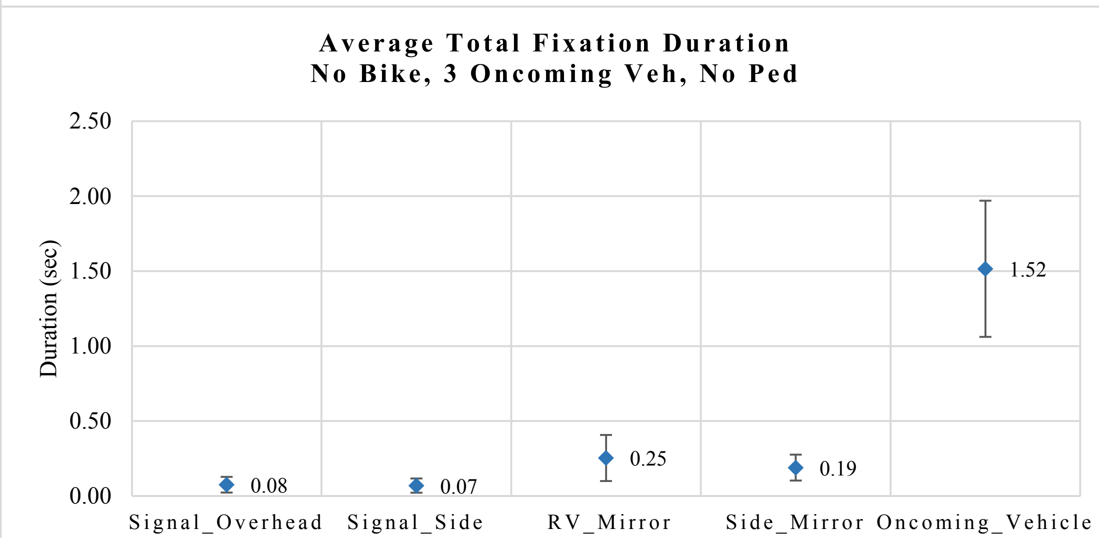

Average Total Fixation Duration
Bike Ahead (16 MPH), 3 Oncoming Veh, No Ped
Duration (sec)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1.34
0.25
0.12
0.28
0.29
1.97
Bicyclist
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror
Oncoming Vehicle

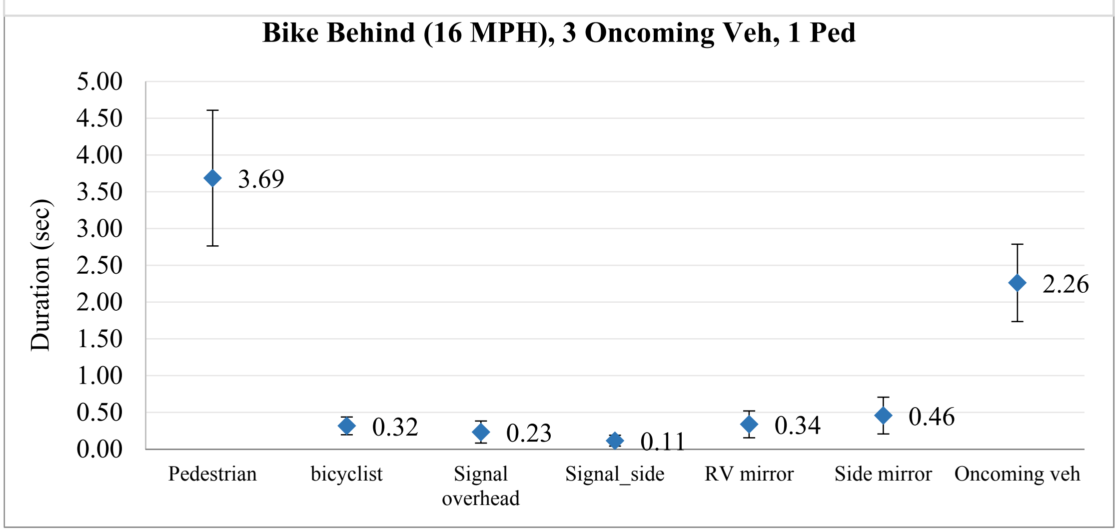

Average Total Fixation Duration
Bike Ahead (10 MPH), No Oncoming Veh, 1 Ped
Duration (sec)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
3.34
1.80
0.12
0.16
0.57
0.40
Pedestrian
bicyclist
Signal overhead
Signal_side
RV mirror
Side mirror

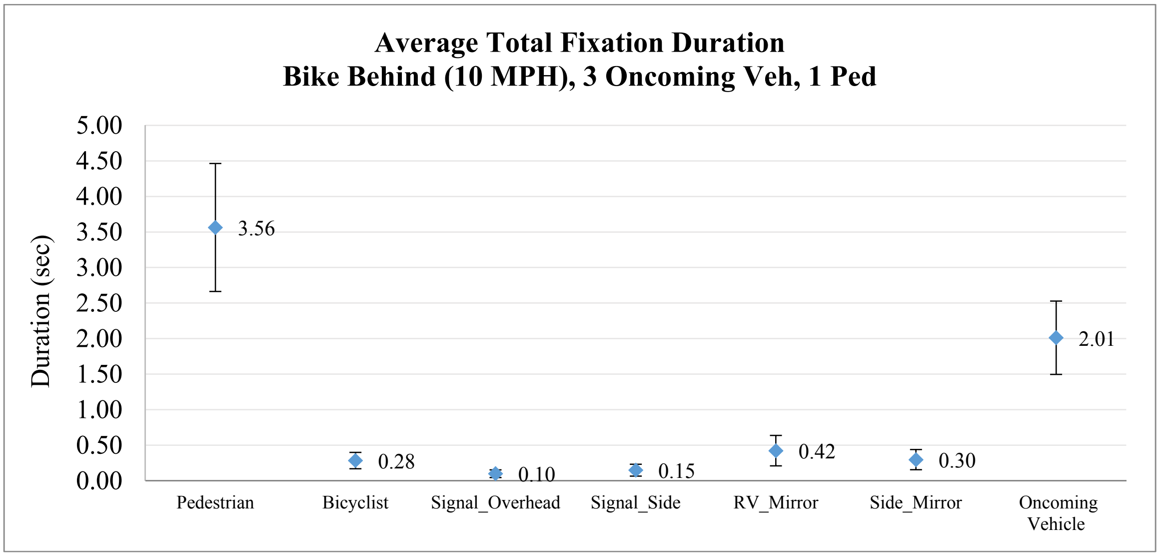

Average Total Fixation Duration
No Bike, No Oncoming Veh, 1 Ped
Duration (sec)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4.61
0.11
0.28
0.57
0.32
Pedestrian
Signal overhead
Signal_side
RV mirror
Side mirror

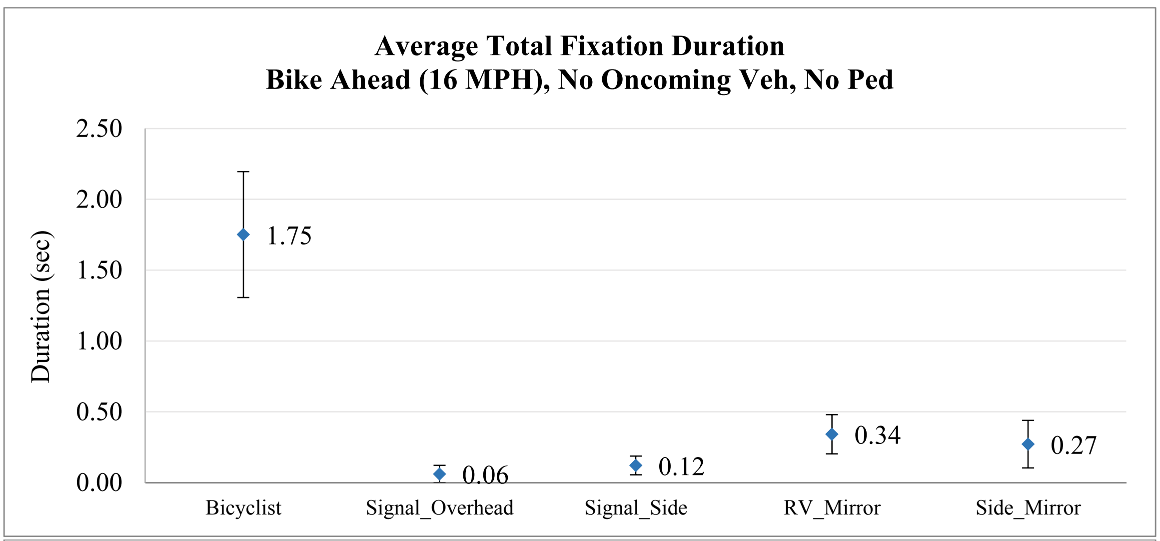

Average Total Fixation Duration
Bike Ahead (10 MPH), No Oncoming Veh, No Ped
Duration (sec)
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
1.37
0.08
0.12
0.56
0.37
bicyclist
Signal overhead
Signal_side
RV mirror
Side mirror

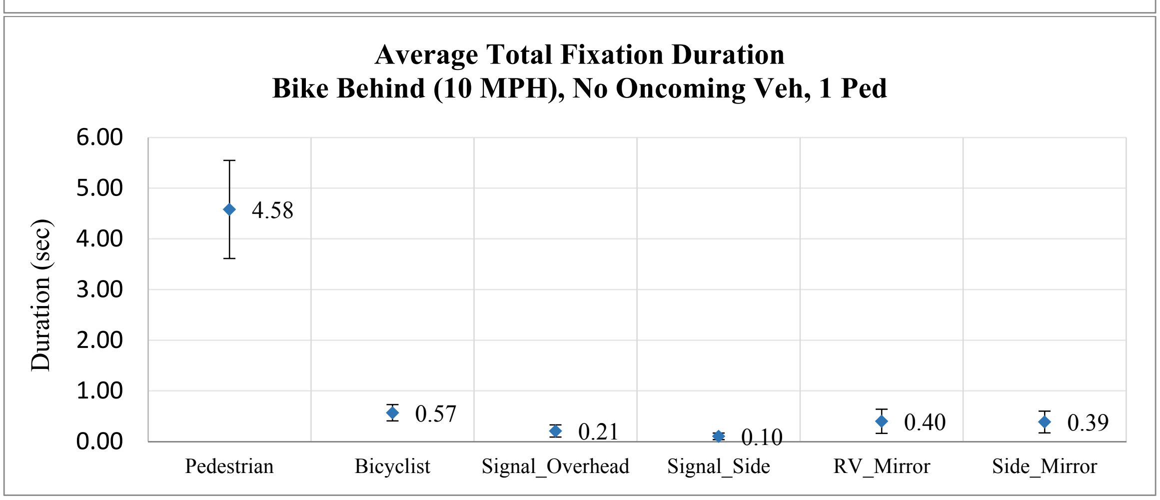

Average Total Fixation Duration
Bike Behind (10 Mph), 3 Oncoming Veh, No Ped
Duration (sec)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.16
0.21
0.10
0.31
0.57
1.79
Bicyclist
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror
Oncoming Vehicle

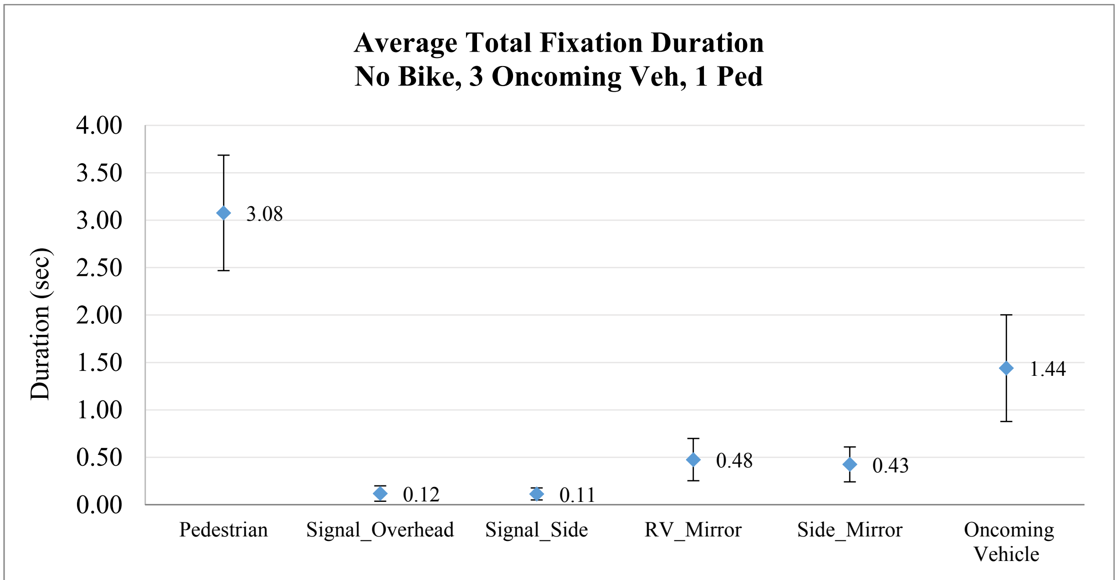

Average Total Fixation Duration
No Bike, 3 Oncoming Veh, No Ped
Duration (sec)
2.50
2.00
1.50
1.00
0.50
0.00
0.08
0.07
0.25
0.19
1.52
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror
Oncoming_Vehicle

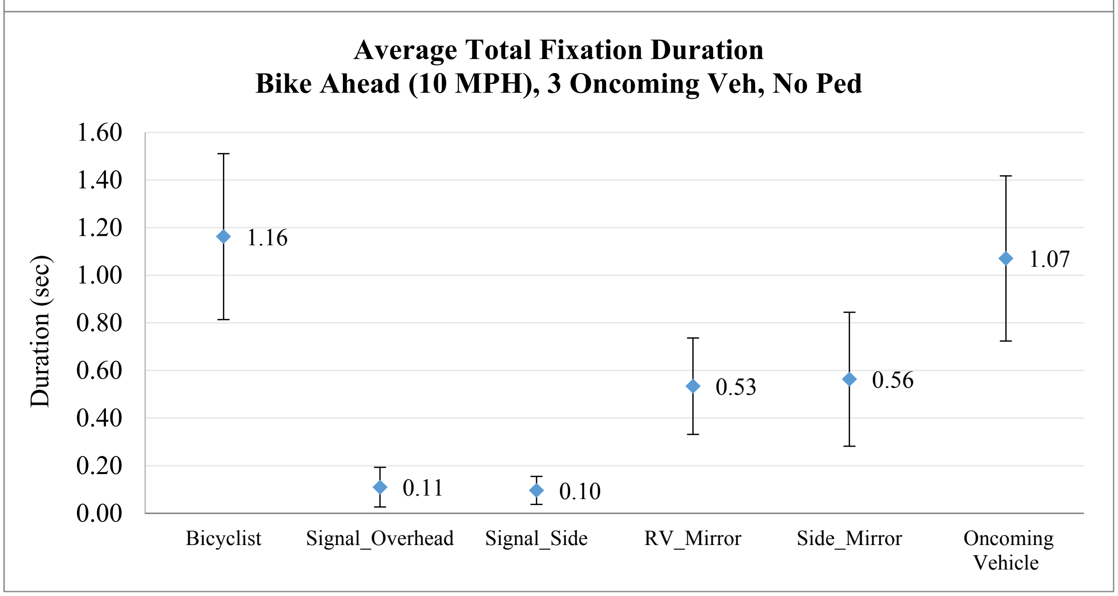

Bike Behind (16 MPH), 3 Oncoming Veh, 1 Ped
Duration (sec)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
3.69
0.32
0.23
0.11
0.34
0.46
2.26
Pedestrian
bicyclist
Signal overhead
Signal_side
RV mirror
Side mirror
Oncoming veh


Average Total Fixation Duration
Bike Behind (10 MPH), 3 Oncoming Veh, 1 Ped
Duration (sec)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
3.56
0.28
0.10
0.15
0.42
0.30
2.01
Pedestrian
Bicyclist
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror
Oncoming Vehicle


Average Total Fixation Duration
Bike Ahead (16 MPH), No Oncoming Veh, No Ped
Duration (sec)
2.50
2.00
1.50
1.00
0.50
0.00
1.75
0.06
0.12
0.34
0.27
Bicyclist
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror


Average Total Fixation Duration
Bike Behind (10 MPH), No Oncoming Veh, 1 Ped
Duration (sec)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
4.58
0.57
0.21
0.10
0.40
0.39
Pedestrian
Bicyclist
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror


Average Total Fixation Duration
No Bike, 3 Oncoming Veh, 1 Ped
Duration (sec)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
3.08
0.12
0.11
0.48
0.43
1.44
Pedestrian
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror
Oncoming Vehicle


Average Total Fixation Duration
Bike Ahead (10 MPH), 3 Oncoming Veh, No Ped
Duration (sec)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1.16
0.11
0.10
0.53
0.56
1.07
Bicyclist
Signal_Overhead
Signal_Side
RV_Mirror
Side_Mirror
Oncoming Vehicle

APPENDIX E

SAGAT QUESTIONNAIRE

APPENDIX E: SAGAT Questionnaire

SAGAT questionnaire

Subject number?

Q1 How many opposing vehicles turned at the last intersection ahead of you?

- ❍ No vehicles
- ❍ One vehicle
- ❍ Two vehicles
- ❍ Do Not Know

Q2 How many bicyclists did you pass on or were behind you just before you turned right at the last intersection?

- ❍ No bicyclists
- ❍ One bicyclist
- ❍ Two bicyclists
- ❍ Do Not Know

Q3 What was the last road sign you saw before you turned right at the last intersection?

- ❍ Speed limit
- ❍ Stop sign
- ❍ Railroad
- ❍ Bike lane sign
- ❍ Pedestrian crossing sign
- ❍ Do Not Know

Q4 Upon arriving at the last intersection, what movement do the vehicles waiting across from you intend to make?

- ❍ No opposing vehicle
- ❍ All vehicles would turn right
- ❍ All vehicles would turn left
- ❍ All vehicles would go straight
- ❍ Some would go straight, some would turn left
- ❍ Some would go straight, some would turn right
- ❍ Do Not Know

Q5 In what direction is the location your vehicle started this drive from when the simulation stopped?
- To the left
- To the right
- In front of me
- Behind me
- Do Not Know

Q6 How far are you from the last intersection you turned at?
- Less than 100 feet
- 100-150 feet
- 151-250 feet
- 251-350 feet
- More than 350 feet
- Do Not Know

Q7 Suppose that the simulation was not stopped, do you think the pedestrian would finish crossing the intersection by the time you reach the intersection driving at the posted speed limit?
- No pedestrians
- Yes
- No
- Do Not Know

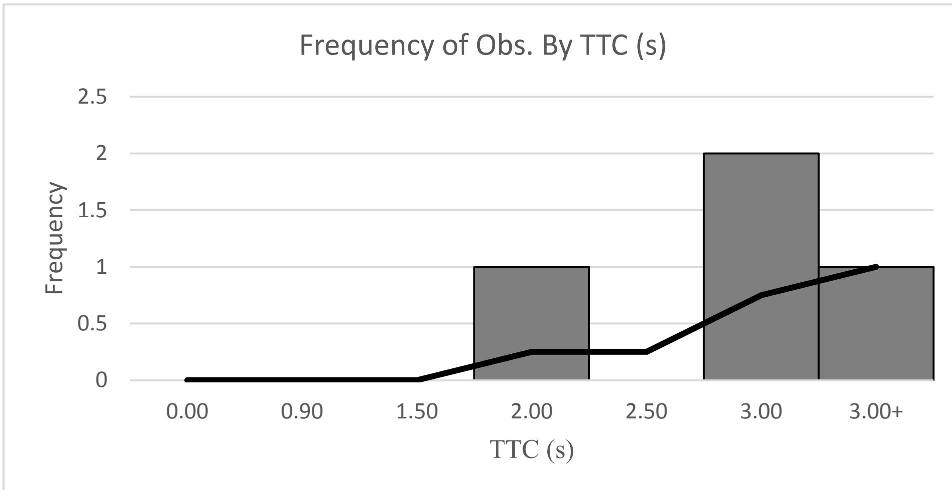
Q8 Suppose that the simulation was not stopped, how long would it take to reach the stop line of the approaching intersection driving at the posted speed limit?
- Less than 10 seconds
- 10 - 30 seconds
- 30 seconds -1 minute
- 1–2 minutes
- 2–3 minutes
- More than 3 minutes
- Do Not Know

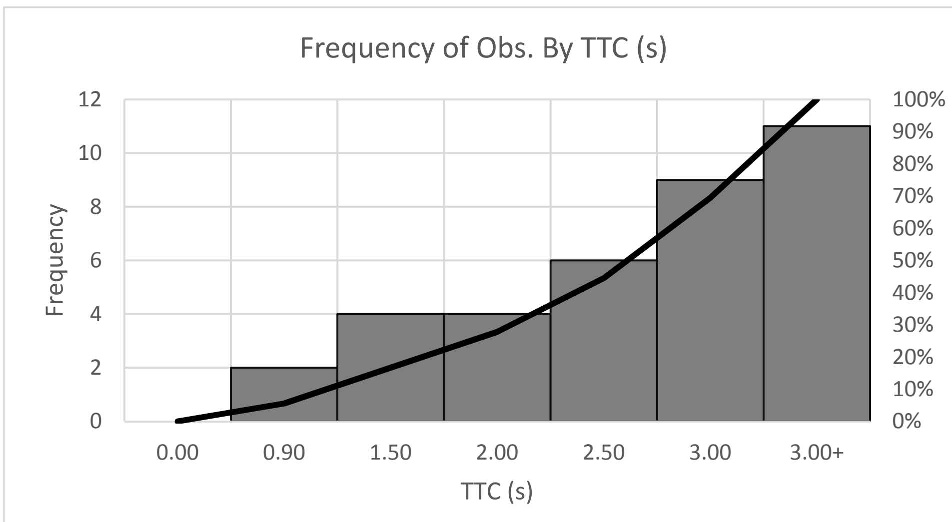
Q9 How far would you have to drive to reach the intersection from the point you stopped?
- Less than 100 feet
- 100-150 feet
- 151-250 feet
- 251-350 feet
- More than 350 feet
- Do Not Know

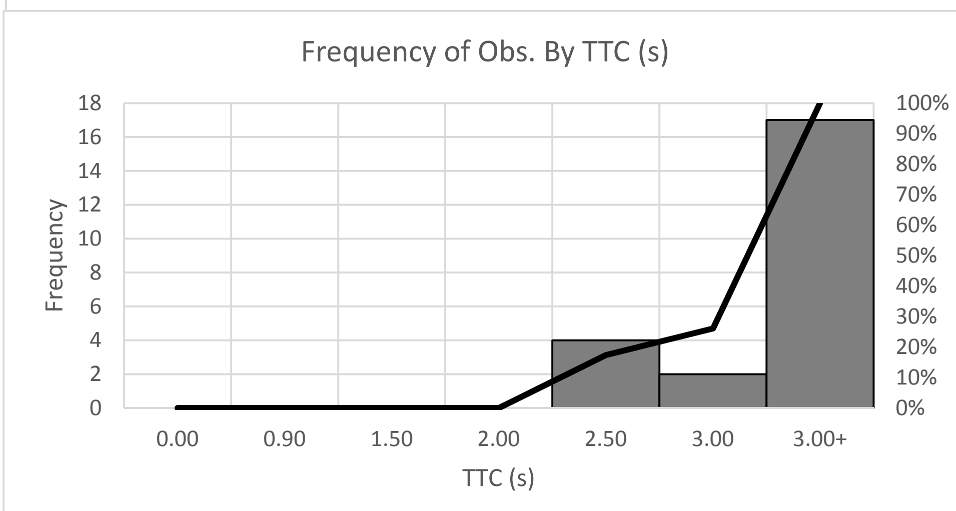
APPENDIX F

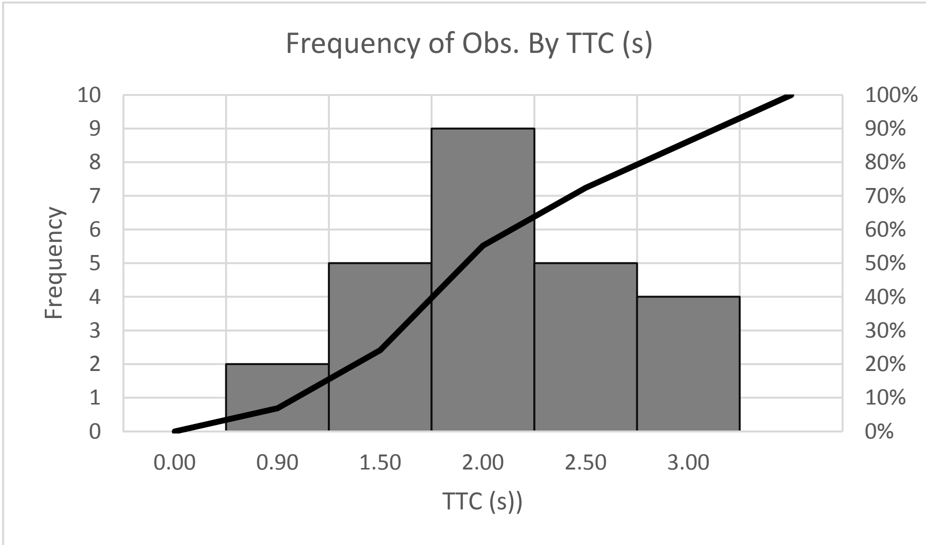
FREQUENCY AND CUMULATIVE FREQUENCY DISTRIBUTION CURVE FOR TRAFFIC CONFLICT INCIDENTS

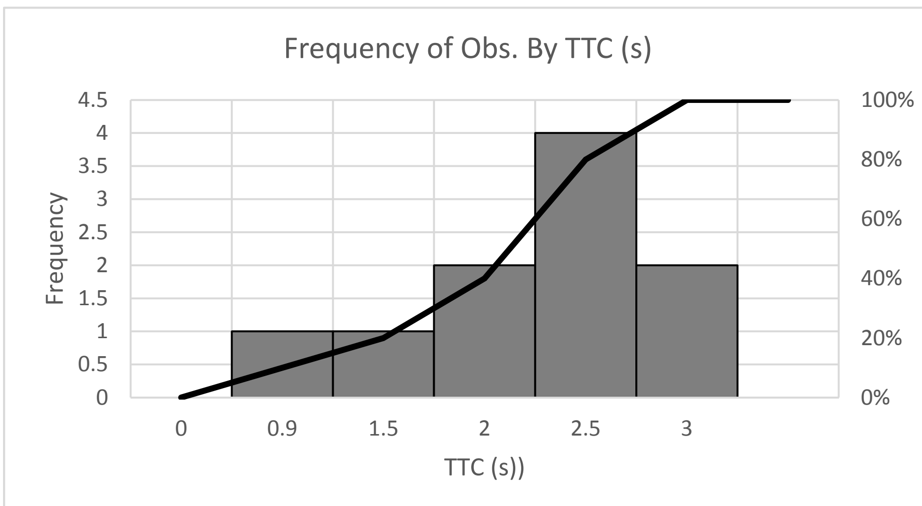
APPENDIX F: Frequency and Cumulative Frequency Distribution Curve for Traffic Conflict Incidents

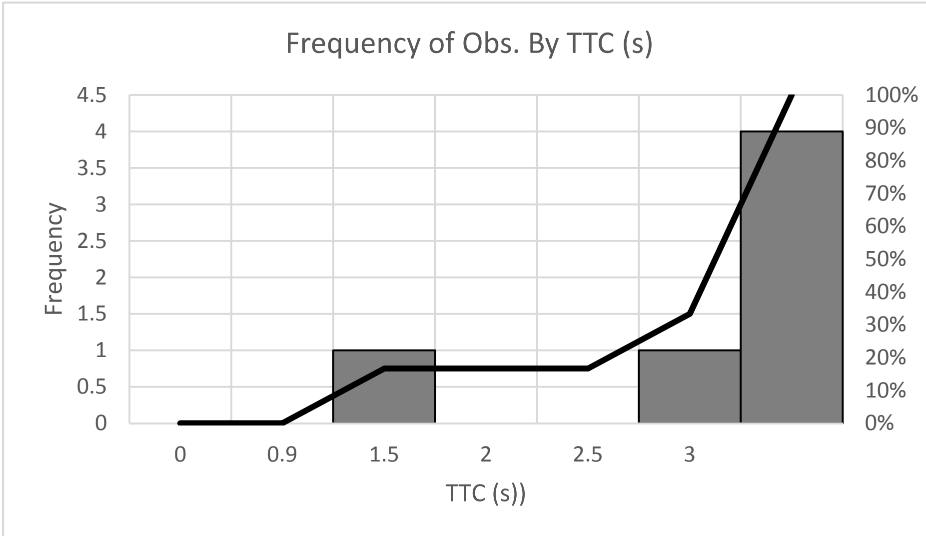


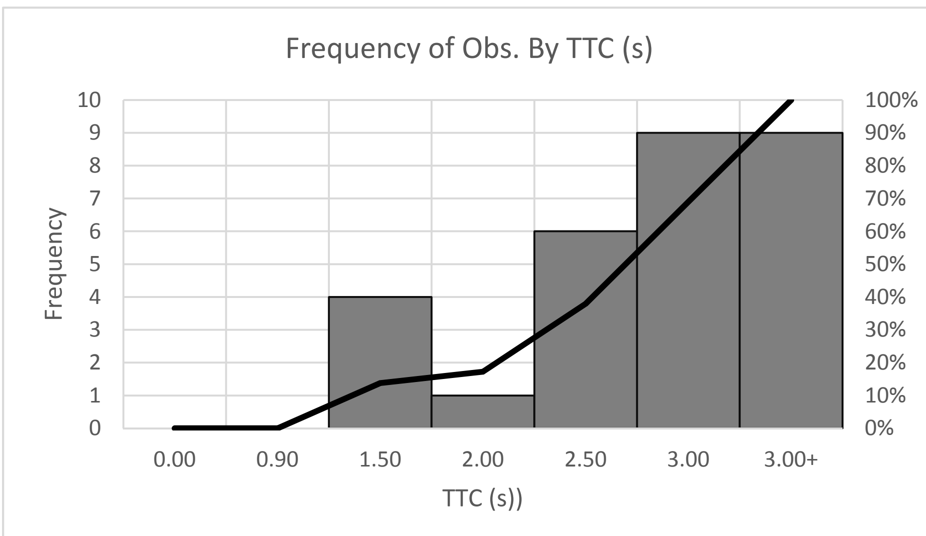





Frequency of Obs. By TTC (s)
Frequency
10
9
8
7
6
5
4
3
2
1
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.00
0.90
1.50
2.00
2.50
3.00
TTC (s))


Frequency of Obs. By TTC (s)
Frequency
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
100%
80%
60%
40%
20%
0%
0
0.9
1.5
2
2.5
3
TTC (s))


Frequency of Obs. By TTC (s)
Frequency
TTC (s))
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0
0.9
1.5
2
2.5
3


Frequency of Obs. By TTC (s)
Frequency
TTC (s))
10
9
8
7
6
5
4
3
2
1
0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.00
0.90
1.50
2.00
2.50
3.00
3.00+