IMPROVED SAFETY AND EFFICIENCY OF PROTECTED/PERMITTED RIGHT TURNS FOR BICYCLES IN THE PACIFIC NORTHWEST

FINAL PROJECT REPORT

by

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16. Abstract

Conflict between bicycles and right-turning vehicles on the approaches to intersections is a critical safety concern in urban environments. To understand the safety and operational implications of using protected-permitted right turns (PPRT), a full-scale bicycling simulator experiment was performed. The velocity and lateral position of bicyclists were evaluated during conflicts between bicycles and right-turning vehicles. Two independent variables were analyzed: the signal indication for right-turning vehicles (circular red or green, solid red or green arrow and flashing yellow arrow) and the pavement markings in the conflict area (white lane markings with no supplemental pavement color and white lane markings with solid green pavement applied in the conflict area). Forty-eight participants (24 women and 24 men) completed the experiment. Signal indications and pavement markings had statistically significant effects on bicycle velocity and lateral position, but these effects varied at different levels of the independent variables. Use of PPRT phasing in conjunction with colored pavement markings was associated with increased bicyclist conflict with right-turning vehicles, whereas PPRT phasing with no supplemental colored pavement markings was associated with improved bicyclist safety. The results provide guidance to transportation professionals about how traffic control devices could be applied to conflict areas before signalized intersections.

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List of Abbreviations

CG: Circular Green
CR: Circular Red
FARS: Fatality Analysis Reporting System
FHWA: Federal Highway Administration
FYA: Flashing Yellow Arrow
NACTO: National Association of City Transportation Officials
NHTSA: National Highway Traffic Safety Administration
OSU: Oregon State University
PPRT: Protected-Permitted Right Turn
PBOT: Portland Bureau of Transportation
ROW: Right-of-Way
SDOT: Seattle Department of Transportation
SGA: Solid Green Arrow
SRA: Solid Red Arrow

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Executive Summary

The increasing popularity of bicycling has led to an increase in the frequency of conflicts between bicycles and other vehicles large enough that despite a decrease in the total number of traffic fatalities, the percentage of bicyclist fatalities has increased considerably in recent years. The National Highway Traffic Safety Administration (NHTSA) reported that in 2015, 70 percent of fatal crashes involving bicyclists in the United States occurred in urban areas, among which 28 percent occurred at intersections.

The overall goal of this research was to improve bicyclist safety in the vicinity of urban intersections. Notably, bicyclist performance during conflicts between bicycles and right-turning vehicles on the approaches to signalized intersections was evaluated, and the safety and operational implications of using protected-permitted right turns (PPRTs) in conjunction with colored pavement markings were analyzed.

This research leveraged the high-fidelity bicycling simulator at Oregon State University (OSU). The OSU Bicycling Simulator comprises an instrumented bicycle placed on top of an adjustable stationary platform, with a screen (3.20 m × 2.54 m) that provides the forward view (visual angle: width 109° × height 89°, image resolution: 1024 × 768 pixels).

The bicycling simulator experiment was designed to examine conflicts between right-turning vehicles and bicycles by analyzing bicyclist behavior at signalized intersections under different configurations of pavement markings and signal indications. Specifically, 2.5 seconds before the bicyclist reached a conflict area, a right-turning vehicle cut in front of the bicyclist. Bicyclist performance during the conflict was used to evaluate the application of pavement markings and signal indications. A 2×5 factorial design was set up with two levels of bike lane pavement markings and five levels of signal indication. The two levels of pavement marking included 1) white lane markings with no supplemental pavement color ("white lane markings"), and 2) white lane markings with solid green color applied in the conflict area ("solid green"). The five levels of signal indication included 1) circular red (CR), 2) circular green (CG), 3) solid red arrow (SRA), 4) solid green arrow (SGA), and 5) flashing yellow arrow (FYA). Bicyclist performance was measured in terms of velocity (m/s) and lateral position (m). In addition to the simulator experiment, participants were asked to complete a short survey regarding their comprehension of different levels of signal indications for right-turn movements.

The experiment was successfully completed by 48 participants, including 24 women (M_{age} = 29.71, SD_{age} = 10.03) and 24 men (M_{age} = 28.42, SD_{age} = 11.90). Mixed repeated-measures analysis of variance (ANOVA) was used to study the effects of pavement marking and signal indication on bicyclist performance. The primary findings of this study suggest that the following:

- Most participants did not have a correct comprehension of PPRT phasing and the associated right-of-way.
- When the SRA indication was used instead of the CR, with no colored pavement marking (white lane marking only), no difference was observed in bicyclist behavior. However, when solid green pavement markings were applied to the conflict area, bicyclists tended to bike at faster speeds and to divert more toward the travel lane.
- When the FYA indication was used instead of the CG, with no colored pavement marking (white lane marking only), bicyclists biked more slowly and stayed farther away from the travel lane. However, with solid green pavement marking applied to the conflict area, bicyclists biked more quickly and diverted more toward the travel lane.

Introduction

Concerns over effects of motor vehicle use on the environment, neighborhood livability, safety, and health have contributed to a paradigm shift in transportation planning from motorized to nonmotorized modes of transport, which, in turn, has increased the popularity of bicycles. As traffic congestion grows in urban areas, many cities are encouraging bicycling as a functional alternative to automotive use. Bicycling is less infrastructure-intensive than public transportation and has a longer range than walking. Many U.S. cities have plans to increase their bicycle mode share. For example, Seattle, Washington, had a goal of tripling the number of people who commute by bicycle between 2007 and 2017 (SDOT 2007), and Portland, Oregon, adopted a Bicycle Plan that aimed to achieve a 25 percent mode share by 2030 (PBOT 2010). However, the increasing popularity of bicycling has led to a greater frequency of conflicts between bicycles and other vehicles. Figure 1.1 shows that despite a decrease in total number of fatalities, the percentage of bicyclist fatalities has increased considerably in recent years, based on data collected from the Fatality Analysis Reporting System (FARS 2017). The percentage of all fatalities that were due to bicyclist conflicts increased from 1.47 percent in 2003 (42,884 fatalities – 629 bicyclist fatalities) to 2.33 percent in 2015 (35,092 fatalities – 818 bicyclists fatalities).

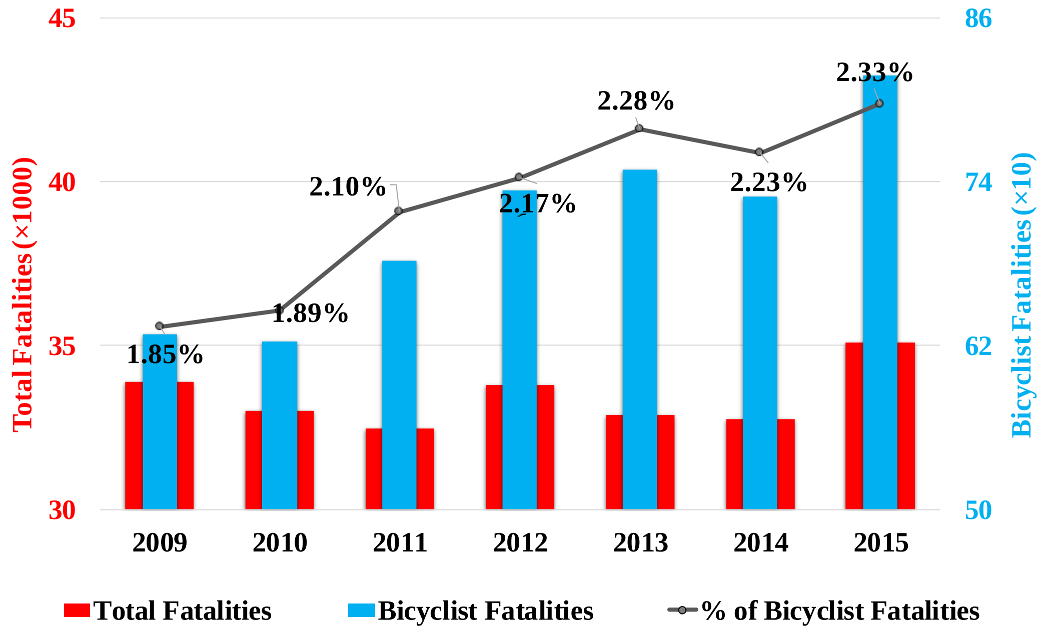

Figure 0.1 Traffic fatality trend

City streets and intersections constitute only a small fraction of the overall area of the surface transportation system. Nevertheless, a comparatively large number of crashes occur on city streets and intersections, which are locations where various transportation modes directly interact, sometimes in conflicting ways. The National Highway Traffic Safety Administration (NHTSA) reported that in 2015, 70 percent of fatal crashes involving bicyclists in the United States occurred in urban areas. Among the bicycle-involved fatal crashes, 28 percent occurred at intersections, 61 percent at non-intersections, and 11 percent at other locations (NHTSA 2017). In Oregon, 960 injuries and eight fatalities were recorded for bicyclists in 2015. More than 69 percent of bicyclist injuries and 25 percent of bicyclist fatalities in Oregon occurred on city streets (ODOT 2017).

Bicyclists in a standard bike lane are often positioned to the right of motorists as they approach an intersection. When an intersection includes an exclusive right-turn bay, the bicyclist will pass a conflict point with right-turning vehicles before the intersection, after which they will be positioned to the left of motorists (fig. 1.2). Although motorists in Oregon must legally yield the right-of-way (ROW) to bicyclists in bicycle lanes, motorists often do not look for bicyclists, look but do not see approaching bicyclists, or misjudge the gap with approaching bicyclists. In addition, bicyclists do not always position themselves to be readily seen, or they approach intersections at high speeds.

Figure 0.2 Conflict area between bicyclists and right-turning vehicles approaching an intersection (Photo credit: Joe Broach, 2017 IBPI Workshop)

The overall goal of this research was to evaluate bicyclist performance during conflicts between bicycles and right-turning vehicles on the approach to signalized intersections, and to analyze the safety and operational implications of using protected-permitted right turns (PPRTs) in conjunction with colored pavement markings. This research leveraged the high-fidelity bicycling simulator at Oregon State University (OSU) to investigate factors contributing to conflicts between bicycles and right-turning vehicles.

This report summarizes the research methods and findings of this project and includes information about the following:

- Literature Review – Summary of PPRT applications, bicyclist behavior, and outcomes of previous bicycling simulation studies
- Experimental Design and Coding of Simulation Test Environment – Development of a statistically sound (counterbalanced factorial experimental design) research approach
- Sampling and Subject Recruiting Plan – Recruitment of 48 study participants
- Simulator Experiment – Testing of experimental design by participants in the OSU Bicycling Simulator
- Analysis of Results – Recording and analysis of data, including instantaneous velocity and lateral position.

Literature Review

This chapter reviews the literature, including design manuals, guidance documents, and published peer-reviewed articles, related to right-turn operations at signalized intersections and provides a detailed description of bicycle simulators and their application. The chapter is organized by topical area and concludes with a summary. No research was found that evaluated flashing yellow arrow (FYA) use in the context of PPRT operations.

1.1 <u>Right Turns at Signalized Intersections</u>

1.1.1 Types of Turning Movements

Right turns at typical signalized intersections can be categorized as right turns that have the ROW, or as right turns that must yield to be consistent with the rules of the road (USDOT 2015). A protected right turn falls into the first category: the ROW is provided, and no conflicting vehicles (or pedestrians) are allowed (USDOT 2015). A permissive right turn falls into the second category: drivers are only allowed to proceed through the intersection if there is an acceptable gap in the conflicting flow of vehicles, including bicycles or pedestrians (USDOT 2015). A protected plus permitted turn is a combination that begins with a protected (or permitted) movement and transitions into a permitted (or protected) movement (USDOT 2015).

1.1.2 Phasing

The *Traffic Signal Timing Manual* defines a traffic signal phase as "a timing process, within the signal controller, that facilitates serving one or more movements at the same time" (USDOT 2015). The *Manual on Uniform Traffic Control Devices* (MUTCD) defines a signal phase as "the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements" (FHWA 2009). The National Electric Manufacturers Association phase numbering system combines right-turn and through movements because they are typically permitted (USDOT 2015). Figure 2.1 shows a typical phasing scheme for an intersection with permitted right-turn movements.

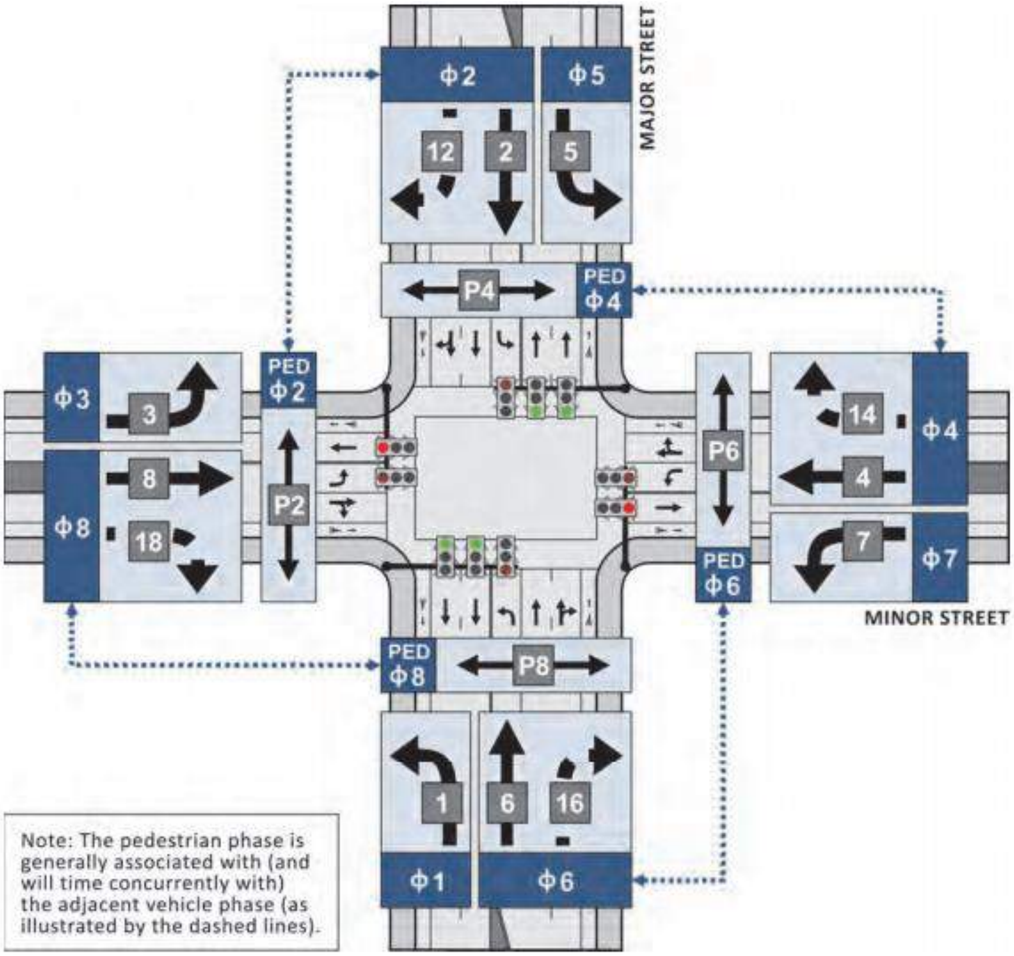

Figure 0.1 General phasing with permitted phasing for right turns (USDOT 2015)

When the right turn is a protected movement, overlap timing can be used (USDOT 2015). A sample phasing scheme is shown in figure 2.2.

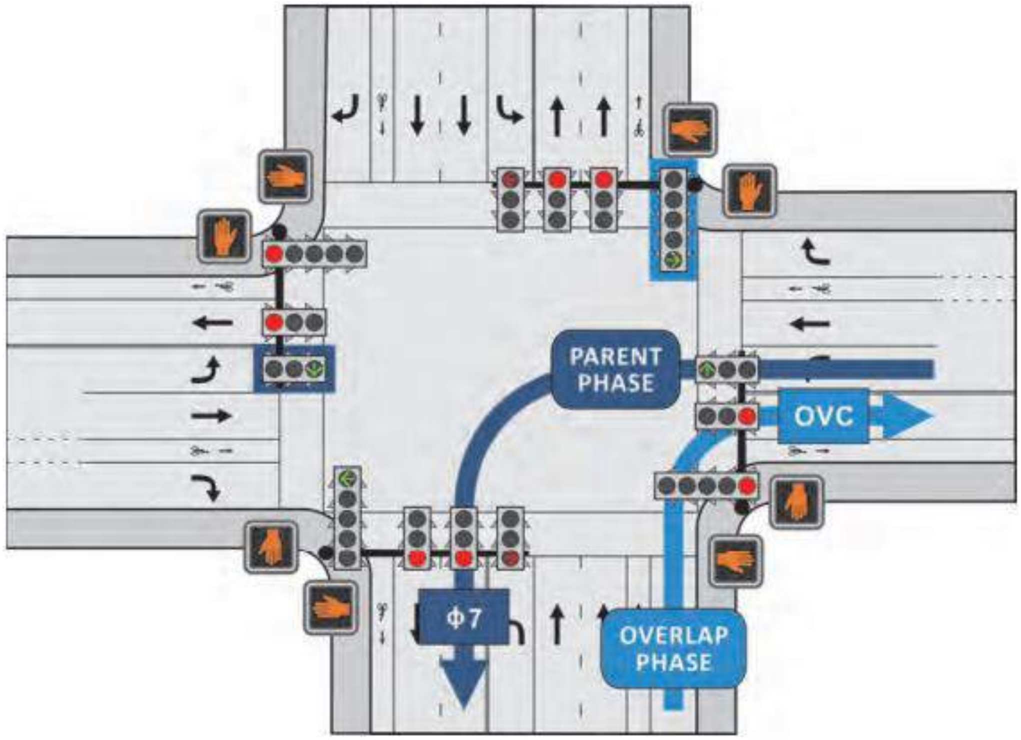

Figure 0.2 Phasing scheme for right-turn overlaps (USDOT 2015)

As described in the *Signal Timing Manual* (USDOT 2015), overlaps are most often used for right-turn movements in the presence of exclusive right-turn lanes. The parent phase is typically the compatible left-turn phase for right-turn overlaps. Some traffic signal controllers allow omission of the right-turn overlap when the conflicting pedestrian phase is active, particularly when the pedestrian phase is associated with the vehicular through-movement. Both the compatible left-turn and adjacent through-movements are parent phases for the right-turn overlap modifier feature. When the conflicting pedestrian phase is assigned to a modifier phase, the right-turn overlap is excluded only when there is a pedestrian call on the adjacent movement. When there is no pedestrian modifier, the right-turn overlap must run adjacent to the through-movement as a permitted movement to avoid conflicts with pedestrians (USDOT 2015). Table 2.1 provides a diagram for typical right-turn overlap settings.

Table 0.1 Typical right-turn overlap settings (FHWA 2015)

Movement number	Overlap letter[1]	Parent phase	Pedestrian modifier phase for right-turn overlap omit (if available)
12	A	2* & 3	2p
14	B	4* & 5	4p
16	C	6* & 7	6p
18	D	8* & 1	8p

[1] Agencies may have different overlap assignments based on their preference.
* These phases should not be included as parent phases if a controller feature to omit right-turn overlap with active conflicting pedestrian phases is not available.

Furth et al. (2014) examined appropriate phasing for right turns and pedestrian/bicycle crossings under conditions of high turn volumes or high speeds, focusing on protected right-turn phasing. They introduced a unique “protected-yet-concurrent” phasing scheme. This scheme, which uses four rings rather than two, allows through-movements to operate at a different time from the turning phase and at the same time as the parallel vehicular through-phase. To illustrate the scheme and determine its likely effects on delay and street footprints, seven examples of concurrent phasing in the United States and the Netherlands were used. The study concluded that the delay and ROW requirements were minimal, and that the complexity of the phasing plans, coordination, and possibility of using re-service would affect phasing performance. Although this phasing scheme requires a right-turn lane, the authors argued that it uses time efficiently and is more efficient and economical than an exclusive pedestrian phasing scheme.

Bui et al. (1991) examined the safety of using partially to fully controlled right-turn phasing at signalized intersections and concluded that fully controlled right-turn phasing significantly reduced the number of right-through crashes at signalized intersections. When phasing was changed from partially to fully controlled, the number of crashes of any type decreased by 65 percent, and the number of right-through crashes decreased by 93 percent (Bui et al. 1991).

1.1.3 Display

Options to support right-turn signal phasing include permitted, protected-permitted, and protected displays (USDOT 2015). As the simplest scheme, the permitted phase is used unless a more complex scheme is needed to improve capacity. If protected phasing is needed, then a separate overlap load switch must be provided for right-turn displays in exclusive right-turn lanes. This modification is preferred over combining the compatible left-turn signal phase with the right-turn arrow indication, as the latter tends to reduce flexibility in signal timing and effectiveness of traffic operations. Right-turn movements are permitted when an adjacent pedestrian phase is called (USDOT 2015). This permission can be signaled with a circular green (CG) indication. When no pedestrians are present, the right-turn movement is protected and can be signaled with a solid green arrow (SGA) (USDOT 2015). The *Signal Timing Manual* states that "if a protected-only display is used with a pedestrian modifier function, the right-turn vehicular movement will be omitted when the conflicting pedestrian phase is called, and a right-turn red arrow will be displayed" (USDOT 2015).

In Oregon, a right-turn movement under a circular red (CR), CG, FYA, or solid red arrow (SRA) indication is permitted after the vehicle has come to a complete stop, unless a posted sign states otherwise. This movement is called a permissive turn (ODOT 2015). Determination of right-turn signal phasing is based on engineering studies and various factors, such as capacity, right-turn volume, and the presence of congestion (or crashes), right-turn lane(s), and conflicting cross walk(s). The permissive right-turn mode is the most commonly used and requires no signal indication. Right-turn movements operate simultaneously with corresponding through-movements but must yield to conflicting pedestrian movement (ODOT 2015).

In the PPRT mode, the right-turn movement is protected during one part of the cycle and permissive during another. The protected portion generally occurs during the complementary left-turn phase, while the permissive portion occurs during the corresponding through-movement phase. The PPRT mode can provide operational benefits during heavy right-turn volumes (ODOT 2015). Figure 2.3 shows an example of PPRT phasing in a ring barrier diagram.

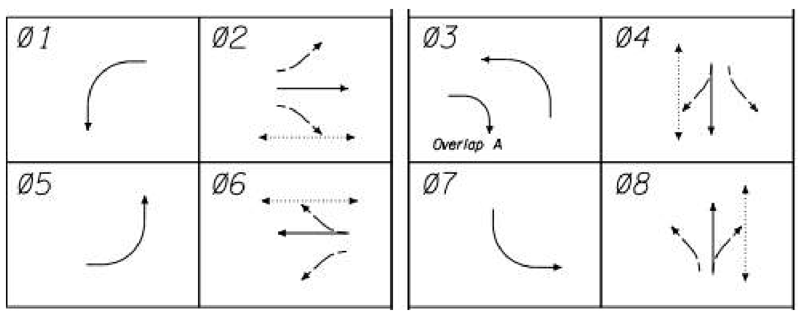

Figure 0.3 Example scheme for PPRT phasing (ODOT 2015)

Protected-only right turns are generally used for exclusive right-turn lanes and can run concurrently with any non-conflicting vehicular or pedestrian movement (ODOT 2015). Traffic may only turn right when presented with an SGA. When a crosswalk is adjacent to the right-turn lane, standard practice is to assign the operating protected right-turn signal to an overlap phase that will not display a green indication concurrently during the walk or flashing Don’t Walk pedestrian intervals (ODOT 2015).

1.1.4 Safety

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).

A recent study for the Oregon Department of Transportation (ODOT) analyzed right-hook crashes (conflicts between right-turning vehicles and through-moving bicycles) during the latter portion of the green phase at signalized intersections (Hurwitz et al. 2015). The study document included an extensive literature review of right-hook crashes, which will not be repeated here. Experiments were jointly conducted by OSU and Portland State University in the OSU Driving Simulator Lab (Jannat 2014). The study concluded that "78 percent of bicyclists were unaware of their stopping position with respect to stopped vehicles queued at an intersection during a red indication, and 19 percent of motorists reported that they would not yield to the adjacent bicyclist approaching from behind if they were detected in rear-view or side-view mirrors" (Jannat 2014). The most common cause of crashes and near-crashes was the driver's failure to search actively for the bicyclist (Hurwitz et al. 2015). Crash and near-crash situations were measured by time-to-collision. Several different intersection treatments (environmental factors, signage, curb radii, pavement markings, and protected intersection designs) were evaluated for their abilities to reduce the frequency and severity of right-hook crashes (Hurwitz et al. 2015). The results showed that motorists were more likely to notice adjacent bicyclists when protected intersection designs were used.

1.2 Pavement Markings for Bicycle Lanes

Pavement markings can be installed to help reinforce routes and directional signage and to provide cyclist positioning and route branding benefits. Pavement markings may be useful where signs are difficult to see (because of vegetation or parked cars) and can help cyclists navigate difficult turns and provide route reinforcement (NACTO 2011). Figure 2.4 illustrates general word, symbol, and pavement markings for bicycle lanes as defined by the MUTCD.

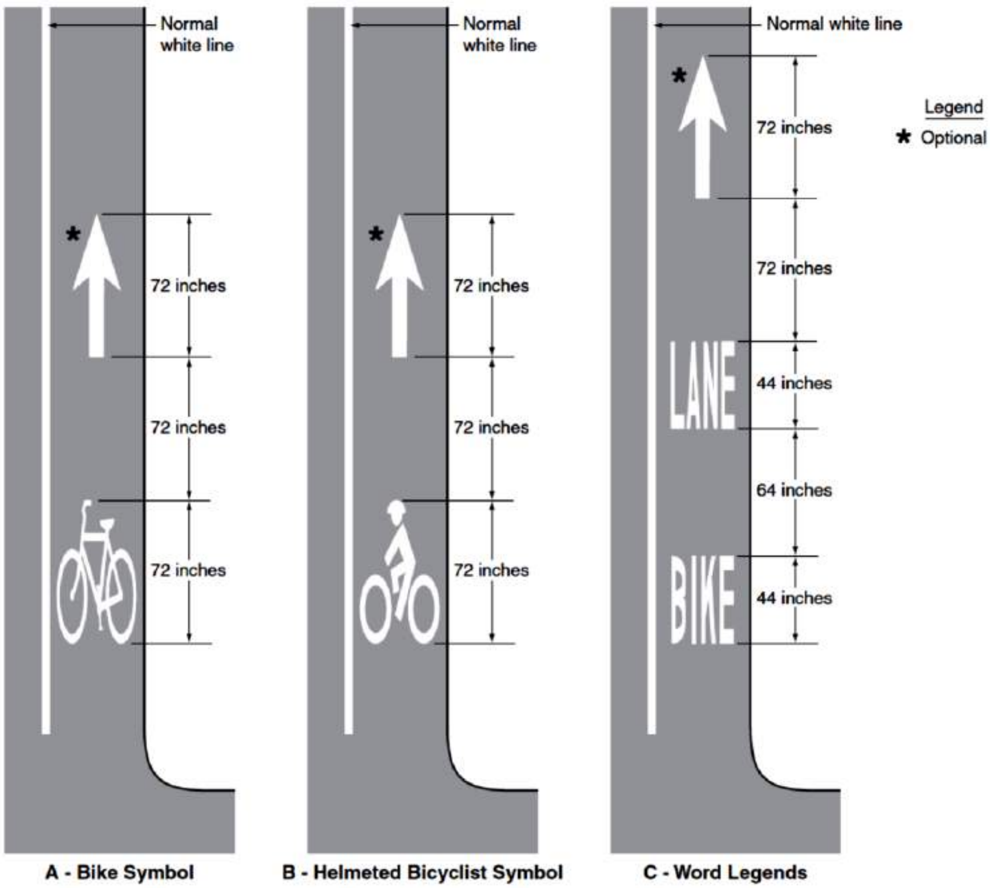

Figure 0.4 Pavement markings for bike lanes in the MUTCD (FHWA, 2009)

Colored pavement within a bike lane increases visibility of the facility, identifies potential areas of conflict, and reinforces priority to cyclists in conflict areas and in areas with pressure for illegal parking. Colored pavement is commonly applied at intersections, driveways, conflict areas, and along nonstandard or enhanced facilities such as cycle tracks (NACTO 2011). Regarding bicycle conflicts with right-turning vehicles, the *Urban Bikeway Design Guide*

(NACTO 2011) identifies three different crossing features that may be used, including a combination of several features (fig. 2.5).

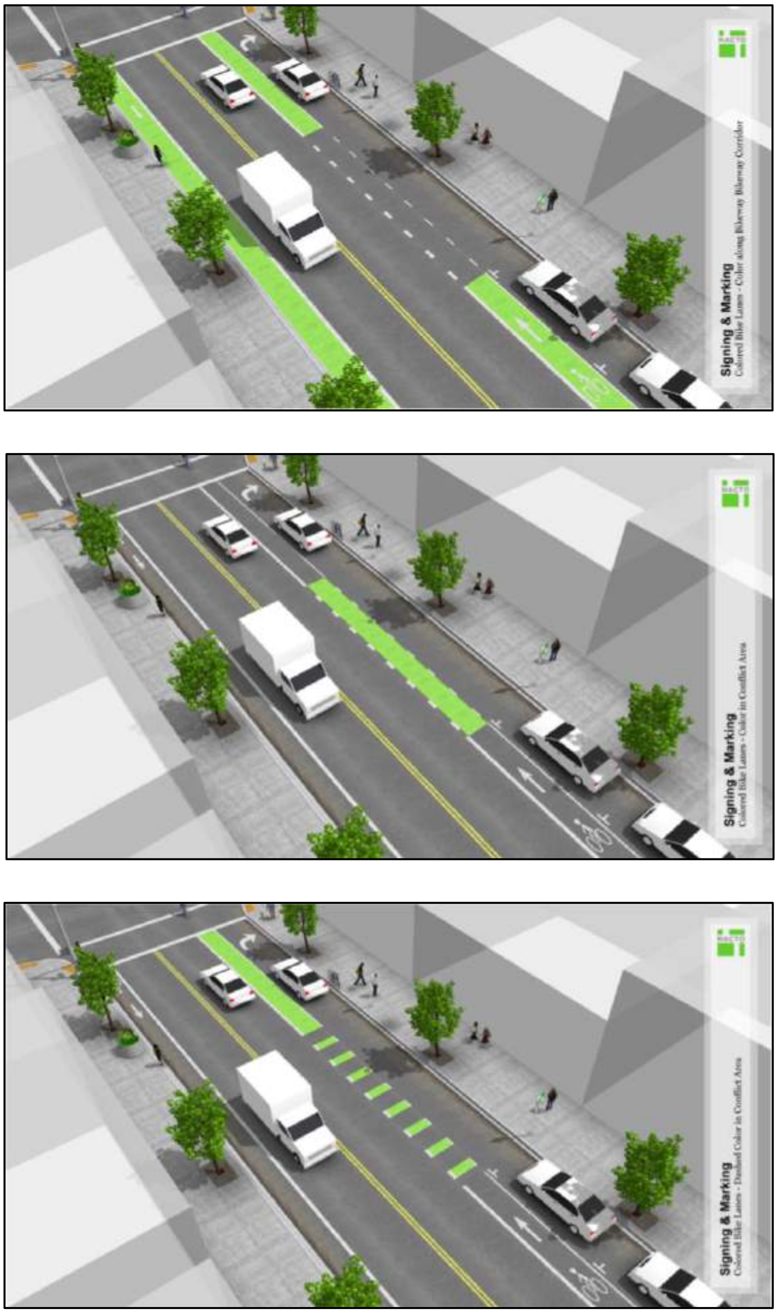

Figure 0.5 Three levels of pavement marking.
Top: White lane markings. *Center:* Solid green. *Down:* Dashed green (NACTO, 2011)

1.3 Bicycle Simulators

Since the emergence of the first primitive flight simulators at the French Ecole de Combat in 1910 (Moore 2008), various automobile, truck, ship, motorcycle, and bicycle simulators have been developed. These simulators are widely used for educational (e.g., research, design, and training) and recreational (e.g., theme parks and video games) purposes. The bicycle simulator has been one of the more challenging simulators to develop because of the inherently unstable dynamics of the bicycle coupled with the dynamics of the human rider, and because of the difficulties associated with the real-time simulation of human-controlled and human-powered vehicles moving in a virtual environment (Kwon et al. 2001). Different forms of bicycle simulators have been utilized in medical science (Deutsch et al. 2012; Ranky et al. 2010; Vogt et al. 2015), sport science (Watson and Swensen 2006), video games (ElectronicSports 2008), and mechanical engineering (He et al. 2005; Hwan et al. 2006). However, very few studies have employed bicycling simulation in the context of transportation safety.

1.3.1 Components of a Bicycle Simulator

The major elements of a typical bicycle simulator include cueing systems (visual, auditory, proprioceptive, and motion), bicycle dynamics, computers and electronics, bicycle frame and control, measurement algorithms, and data processing and storage (fig. 2.6). Cueing systems involve stimulation of all rider sensory and perceptual systems. In each cueing system, the appropriate stimulus resulting from the cyclist's control inputs must be computed and then accurately displayed to the cyclist. Cues, such as steering feel, are a direct consequence of the cyclist's control response and resulting bicycle reaction. Motion cues are a function of the bicycle's dynamic response to rider control inputs, with additional independent inputs due to dynamic roadway disturbances. Visual and auditory cues can result in rider/bicycle responses but also have important independent inputs from dynamic roadway elements (Fisher et al. 2011).

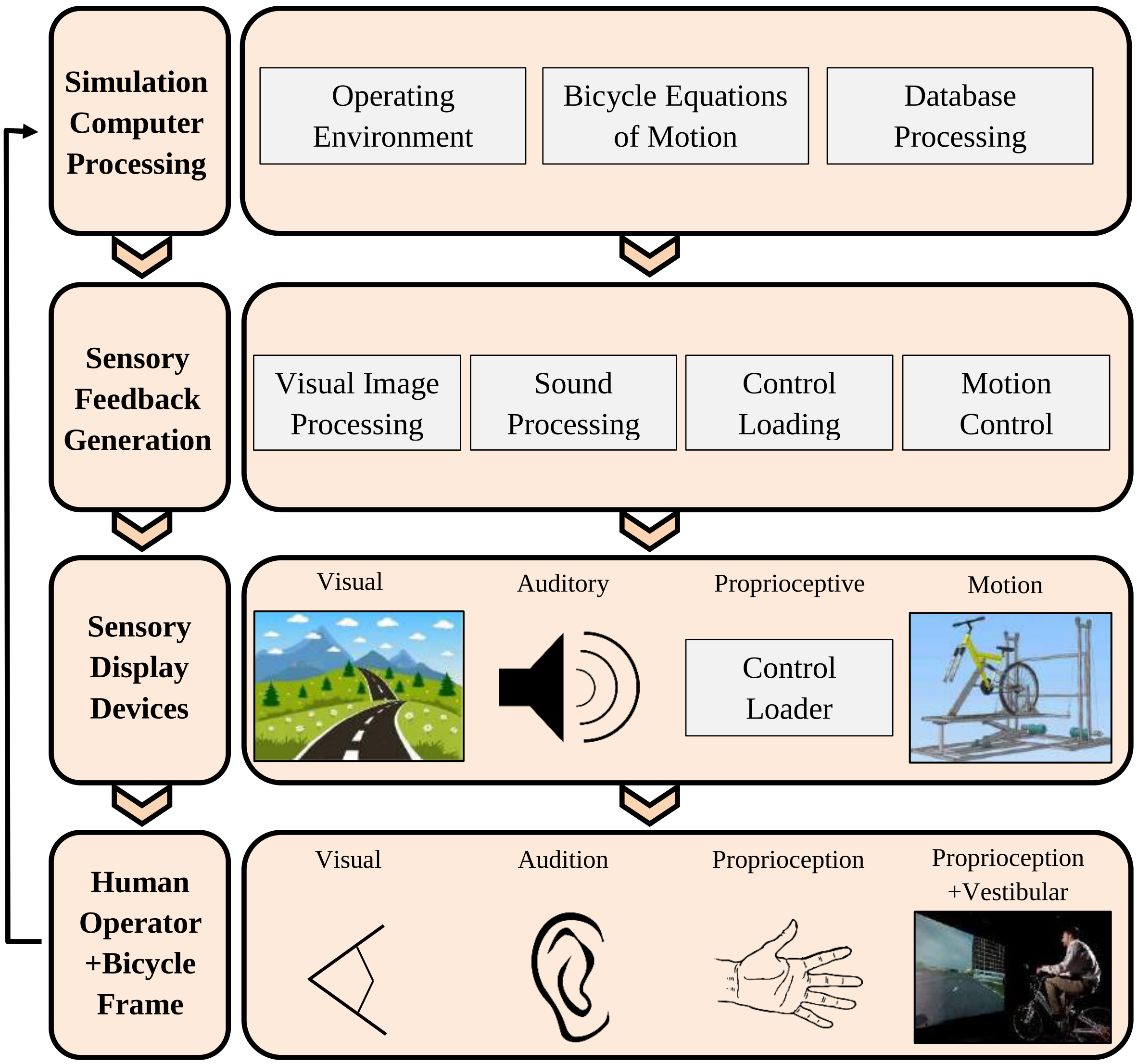

Figure 0.6 Components of a bicycle simulator (adopted from Fisher et al., 2011)

1.3.2 OSU Bicycle Simulator Designs

The OSU Bicycling Simulator consists of an instrumented urban bicycle placed atop an adjustable stationary platform (fig. 2.7). A screen (3.20 m × 2.54 m) provides the forward view with a visual angle of 109° (horizontally) × 89° (vertically) and an image resolution of 1024 × 768 pixels. A small window on the top left corner of the screen acts as a rearview mirror.

Figure 0.7 Bicycle Simulator at OSU

The OSU Bicycling Simulator is one of the first to operate concurrently with a driving simulator, allowing both entities to interact in the same simulated environment, sometimes termed “distributed simulation.” This platform allows for experimentation in which driver and cyclist responses can be simultaneously observed in the laboratory. To increase the demographic variety of subjects, three different bicycles (sized for men, women, and children) are instrumented and can be traded off the adjustable platform.

1.3.3 Bicycle Simulator Applications

In one of the earliest applications of a bicycle simulator in the United States, Plumert et al. (2004) studied children’s road-crossing behavior while bicycling in an immersive virtual environment. Sixty 10- and 12-year-olds and adults were recruited to ride a bicycle mounted on a stationary trainer through a simulated environment consisting of a straight, residential street with six intersections. Their task was to cross all six intersections without being hit by a car.

Participants faced cross-traffic from their left-hand side and waited for gaps they judged to be adequate for crossing. Cross-traffic traveled at a constant speed of 25 or 35 mph with varying temporal gaps between vehicles. Three issues were investigated: 1) whether age differences exist in the size of traffic gaps accepted by 10- and 12-year old children vs. adults, 2) whether children and adults account for the speed of the oncoming traffic when choosing a gap to cross, and 3) whether gap choices relate to crossing behavior.

Five observations were coded at each of the six virtual intersections: 1) whether the cyclist came to a complete stop, 2) the time when the cyclist stopped, 3) the time when the cyclist started moving, 4) the time when the cyclist entered the roadway, and 5) the time when the cyclist cleared the lane of an approaching car. These coded behaviors were used to quantify the crossing behaviors of participants as: 1) stopping, 2) waiting time, 3) gap choice, 4) time left to spare, and 5) start-up time. Results of repeated-measure analysis of variance (ANOVA) tests revealed that although there were no age differences in the gap sizes accepted by children and adults, children left less time to spare between themselves and approaching vehicles. Plumert et al. (2004) concluded that children's gap choices and road-crossing behavior were mismatched relative to adults. Children and adults chose identically sized gaps, suggesting that children and adults did not differ in their perception of temporal (i.e., time to contact) information. However, children had more difficulty than adults coordinating their own movements with those of cars, perhaps due to errors in judging affordance and overestimation of physical ability.

Numerous studies followed Plumert et al. (2004), primarily conducted by the same research team at Hank Lab, investigating different aspects of the road-crossing behavior of child and adult cyclists in a virtual environment (Babu et al. 2011; Chihak et al. 2010; Grechkin et al. 2013; Plumert et al. 2007a; Plumert et al. 2007b; Stevens et al. 2013). For instance, Plumert et al.

(2011) examined how child and adult cyclists' gap choices and movement timing changed over a single experimental session in response to general and specific experiences with crossing traffic-filled intersections in a virtual environment. In that study, 72 participants (36 males, 36 females) in three age groups (10-year-olds, 12-year-olds, and adults; n = 24 per group) participated in a bicycle simulator experiment in which they biked across 12 intersections with continuous cross-traffic from the left-hand side. In the control condition, children and adults encountered randomly ordered gaps ranging from 1.5 to 5.0 seconds at all intersections. In the high-density condition, children and adults encountered a set of intersections with high-density traffic sandwiched between sets of intersections with randomly ordered gaps ranging from 1.5 to 5.0 seconds. Thus, the first four and last four intersections were the same for both groups, but the middle four intersections differed. "General experience" referred to the gap acceptance of the control group between the first and last sets of intersections, and "specific experience" referred to the difference of gap acceptance between the first and last sets of intersections while cyclists were exposed to congested intersections in between.

Plumert et al. (2011) found that gap acceptance shifted in response to both general and specific road crossing experiences. Participants in both conditions were more likely to accept shorter gaps at later intersections than at the initial intersection. This tendency was influenced by the type of previous experience. For example, while both groups nearly always rejected 3.0-second gaps at the first set of intersections, the high-density group was significantly more likely than the control group to accept very short gaps in the last set of intersections. When confronted with high-density traffic, individuals who waited less and accepted shorter gaps were more likely to take very short gaps at subsequent intersections even though bigger gaps were readily available. With respect to this road-crossing task, they found that 10-year-olds were more adaptive and had more room for improvement than 12-year-olds.

In an extensive study, Liu et al. (2012) investigated the response patterns of 58 young cyclists (29 male and 29 female) to a right-turning motorcycle using a bicycle simulator. Scenarios were developed in which a motorcycle made a right turn ahead of the cyclist. Two factors (speed difference and cut-in time gap) were generated, each at three levels, making nine different experimental scenarios. Distributions of the mean and standard deviation for steering angle and speed were analyzed in a series of mixed repeated-measure ANOVA tests with gender as a between-subject factor and speed difference and cut-in time gap as within-subject factors. A *k*-means cluster analysis was performed to investigate response patterns characterized jointly by speed measurements. In this way, all 522 experimental conditions were assigned to five clusters: early response and quickly depress the brake, last-moment response and slowly depress the brake, late response and quickly depress the brake, very late response and quickly depress the brake, and no response. For each participant, the four measurements were calculated from the time that the motorcycle started to cut in until the time that the motorcycle started to turn right.

Liu et al. (2012) found that for shorter cut-in time gaps, the steering angles were small and deflected to the right to avoid the passing motorcycle, the speeds were lower, and the steering angle and speed variations were larger. However, for larger speed differences, the number of steering angle and speed variations was unexpectedly lower. Furthermore, the larger speed difference conditions and the no-response pattern resulted in two collisions. Investigating these two accidents, Liu et al. stated that less experienced, younger cyclists may not associate speed differences with danger, and that they may judge the situation of higher speed difference as safer than it is and not respond in a timely manner.

In one recent application of a bicycle simulator, Caro and Bernardi (2015) investigated the role of sensory cues in speed perception in a virtual environment. Twelve volunteers aged 21 to 46 years participated in the experiment, which included reference, reduced visual speed, reduced force feedback, and reduced airflow conditions. In the reference condition, sensory cues were consistent with the cyclist's own speed; in the three other conditions, the sensory cues were manipulated. A change in visual speed or force feedback affected the speed of participants: the increase in speed produced by participants reflected the decrease in the perceived speed. Although most participants indicated that they were using airflow as a cue, airflow had no effect on produced speed. However, on the basis of the small difference observed in produced speed, the authors concluded that the main sensory cues were not manipulated in their experiment. They suggested that the gear ratio and pedaling cadence could be the main sensory cues to manipulate.

1.4 Literature Review Summary

- The planning, design, and operation of signalized intersections are complex processes that require the balancing of safety and efficiency for all system users. Although the FYA is allowed for PPRT operations, there has been no previous research on the operational or safety implications of PPRT phasing.
- The *Urban Bikeway Design Guide* (NACTO 2011) suggests the use of colored pavement markings for bicycle intersection crossings.
- Bicycle simulators have been utilized in medical science, sport science, video games, and mechanical engineering, but very few studies have employed bicycling simulation in the context of transportation safety. In the traffic and transportation engineering domain, bicycle simulators are mostly employed to investigate traffic safety issues, such as the

gap acceptance and road-crossing behavior of children while bicycling and the response of cyclists to right-turning motorcycles.

Method

This section describes the hardware and software associated with the OSU Bicycle Simulator; the data types collected for the bicycling simulator experiment; and the experimental protocol, including the process for subject recruitment, the sequence of activities performed by participants during the experiment, and the pilot study of the experimental protocol.

1.5 Experimental Equipment

The experimental design and established experimental protocols were selected as the most appropriate means to address the research questions of interest. This approach was grounded in accepted practice (Fisher et al. 2011) and leveraged unique research capabilities at OSU. The primary tool for this experiment, the OSU Bicycling Simulator, is described in detail below.

1.5.1 Bicycling Simulator

The OSU Bicycling Simulator comprises an instrumented bicycle placed on top of an adjustable stationary platform, with a screen (3.20 m × 2.54 m) that provides the forward view (visual angle: width 109° × height 89°, image resolution: 1024 × 768 pixels). A small window on the top left corner of the screen acts as a rearview mirror.

Researchers build the simulated environment and track subject bicyclists from within the operator workstation (fig. 3.1), in a separate room out of the view of participants in the bicycle simulator experiment. The update rate for projected graphics is 60 Hz. Ambient sounds around the bicycle are modeled with a surround sound system. The computer system comprises a quad core host running Realtime Technologies SimCreator Software with a graphics update rate of 60 Hz. The simulator software captures and outputs highly accurate values for performance measures such as bicycle speed, position, and acceleration.

Figure 0.1 Operator workstation for the bicycling simulator.
Left: Real-time monitoring of the simulated environment. *Right*: Researcher designing an experiment in SimCreator

Figure 3.2 shows views of the simulated environment created for this experiment from the participant's view (left) and outside view (right).

Figure 0.2 Simulated environment in the OSU Bicycle Simulator.
Left: Participant's perspective. *Right:* Outside view, with researcher checking the bicycle brake

The virtual environment was developed in simulator software packages, including Internet Scene Assembler, SimCreator, AutoCAD, and Google Sketchup. The simulated test track was developed in Internet Scene Assembler by using Java Script-based sensors on test tracks to display dynamic objects, such as a truck cutting in front of a bicyclist or a pedestrian walking on the sidewalk.

1.5.1.1 Simulator Data

Several parameters related to the subject bicycle and dynamic objects were recorded at roughly 10 Hz (10 times a second) throughout the experiment:

- Time was recorded to map changes in speed and acceleration with the position on the roadway.
- Instantaneous speed of the subject bicycle was recorded to identify the change in speed as the bicyclist approached an intersection.
- Instantaneous position of the subject bicycle was recorded to estimate the headway and distance upstream from the stop line.
- Instantaneous acceleration/deceleration was recorded to identify any acceleration or deceleration as the bicyclist approached an intersection.
- Instantaneous speed of the dynamic vehicle was recorded to identify the speed as the bicyclist approached the intersection.
- Instantaneous position of a dynamic object was recorded to locate the distance upstream from the stop line and to calculate the headway of the subject bicycle; and
- SimObserver data, obtained from three cameras positioned at various viewing angles on the simulator, were obtained to observe the actions of participants approaching a signalized intersection.

Figure 3.3 shows the various camera views and screen captures that were recorded by SimObserver (Version 2.02.4).

Figure 0.3 Screenshot of the three views from SimObserver.
Left: Simulated scene as projected on the screen. *Center:* View of the driver's upper body and hands on the handlebar. *Right:* View of the entire simulator platform

1.5.1.2 Simulator Sickness

Simulator sickness is a phenomenon wherein a person exhibits symptoms of motion sickness, such as headache, nausea, dizziness, sweating, and in extreme situations, vomiting, associated with simulator use (Fisher et al. 2011; Owens and Tyrrell 1999). 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 and physical motion cues, as perceived by the vestibular system (Owens and Tyrrell 1999). There was no literature to suggest that simulator sickness would or would not occur in bicycle simulation experiments. However, it was considered to be a possibility in this study to ensure the highest level of comfort for all participants.

1.6 Experimental Design

The bicycling simulator experiment was designed to examine conflicts between right-turning vehicles and bicycles by analyzing bicyclist behavior at signalized intersections. Specifically, 2.5 seconds before the bicyclist reached a conflict area, a right-turning vehicle cut in front of the bicyclist. Bicyclist performance was used to evaluate different pavement markings and signal indications.

1.6.1 Factorial Design

The experiment tested two independent variables: pavement markings and signal indications (table 3.1).

Table 0.1 Experimental factors and levels

Variable name	Level	Level description
Pavement marking	1	White lane marking
	2	Solid green
Signal indication	1	Circular red (CR)
	2	Circular green (CG)
	3	Solid red arrow (SRA)
	4	Solid green arrow (SGA)
	5	Flashing yellow arrow (FYA)

For pavement marking levels, recommendations from the National Association of City Transportation Officials (NACTO) *Urban Bikeway Design Guide* (2011) were considered. Two levels of bike lane pavement markings were used (fig. 3.4): 1) white lane markings with no supplemental pavement color (called "white lane markings" hereafter), and 2) white lane markings with solid green color applied in the conflict area (called "solid green" or "solid green pavement" hereafter). Five levels of signal indication were considered: 1) CR, 2) CG, 3) SRA, 4) SGA, and 5) FYA.

Figure 0.4 Two levels of pavement marking (adopted from NACTO, 2011).
Left: White lane markings. *Right:* Solid green

These independent variables (factors) and levels resulted in a study with a 2×5 factorial design. The roadway cross-section included two 12-ft travel lanes with 6-ft bicycle lanes in each direction. An 8-ft parking lane interrupted by a 12-ft right turn bay was created in one direction to account for conflicts between bicycles and right-turning vehicles.

1.6.2 Research Questions

Bicyclist performance was measured in terms of velocity (m/s) and lateral position (m). The potential influence of the experimental factors (table 3.1) on each response variable formed the basis of the research questions regarding bicyclist performance.

- *Research Question 1 (RQ1)*: Do pavement markings and signal indications affect the velocity of the bicyclist?
- *Research Question 2 (RQ2)*: Do pavement markings and signal indications affect the lateral position of the bicyclist?

1.6.3 Presentation of Bicycling Scenarios

Ten scenarios (table 3.2) were presented to participants across four grids, with participants exposed to various treatment configurations to measure their influence.

Table 0.2 Cut-in scenarios

Experiment #	Cut-in #	Pavement marking	Signal indication
Grid 1			
2	1	White lane marking	CG
6	-		-
5	2		FYA
Grid 2			
4	1	White lane marking	SGA
1	2		CR
3	3		SRA
Grid 3			
2	1	Solid green	CG
6	-		-
4	2		SGA
Grid 4			
1	1	Solid green	CR
3	2		SRA
5	3		FYA

Figure 3.5 shows an example grid layout. Participants began at the start line and rode through three loading zones. The bicyclist was prompted to stop pedaling at the finish line, at which point the researcher terminated the simulation.

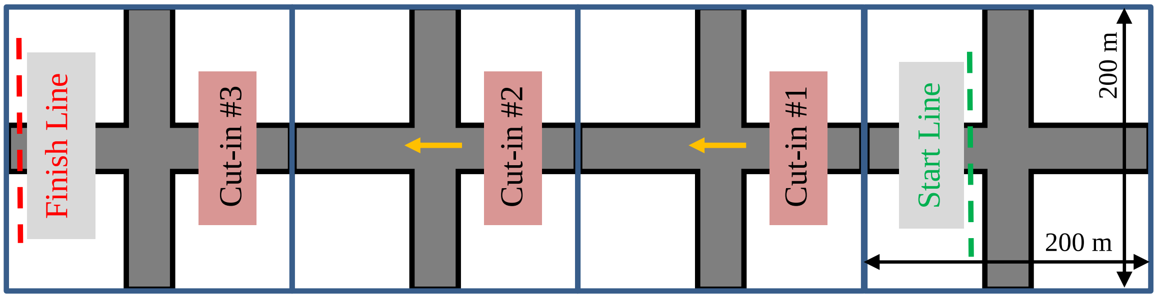

Figure 0.5 Example grid layout

1.6.4 Counterbalancing

To control for practice or carryover effects, the order of intersection grids was counterbalanced. Six different grid sequences were chosen through a randomized partial counterbalancing procedure. The grid sequences were as follows: 3-1-4-2, 1-2-4-3, 2-4-1-3, 4-1-2-3, 3-4-2-1, and 1-3-4-2.

1.7 <u>Bicycling Simulator Experimental Protocol</u>

1.7.1 Recruitment

Participants were selected on the basis of information on the typical demographics of the bicyclist population, available through researcher contacts at bicycle clubs and through nonmotorized user and demographic surveys completed by regional and national transportation departments. Participants were required to have ridden a bicycle, to be physically and mentally capable of appropriately controlling a bicycle, to be competent to provide informed consent, and to not have vision problems that would prevent them from participating in this study. Participants were excluded if they used glasses while cycling; however, contact lenses were acceptable.

The simulator study had a maximum enrollment of 100 participants (50 males, 50 females). Researchers did not screen interested participants on the basis of gender until the quota for either gender was reached, at which point only participants of the gender with the unmet quota were enrolled. Although it was expected that many participants would be OSU students because of the lab being located on the OSU campus, an effort was made to incorporate participants of all ages within the specified age range of 18 to 75 years. Throughout the entire study, information related to 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.

1.7.2 Informed Consent and Compensation

Upon their arrival to the laboratory, the participant was presented with the informed consent form (OSU IRB approval no. 7517). The researcher explained the overall idea of the entire experiment to the participant, who was invited to ask questions regarding the test. The informed consent document described the reasoning behind the study, the importance of volunteer participation, and the risks and benefits to the participant. Participants were given $20 cash compensation for participating in an experimental trial after signing the consent document.

1.7.3 Prescreening Survey

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

- Vision – Good vision was crucial for the test. Participants were asked whether they used corrective glasses or contact lenses while driving/bicycling. During the test ride, it was ensured that participants could see the bicycling environment clearly and could read the visual instructions displayed on the screen.

- Simulator sickness – Participants with previous driving/bicycling simulation experience were asked about any simulator sickness they had experienced. If they previously had experienced 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 toward any kind of motion sickness, they were encouraged not to participate in the experiment.

1.7.4 Calibration Ride

A test ride followed completion of the prescreening survey. Bicyclists performed a 3- to 5-minute calibration ride to acclimate to the operational characteristics of the bicycling simulator and to determine whether they were prone to simulator sickness. Participants were instructed to ride and follow all traffic laws as they normally would. The test ride was conducted on a generic city environment track with turning maneuvers that were like those in the experiment, so that participants could become accustomed to the mechanics of the bicycle and the virtual reality of the simulator (fig. 3.6). If a participant reported simulator sickness during or after the calibration ride, then s/he was excluded from the experimental rides.

Figure 0.6 Calibration ride in simulation

1.7.5 Experimental Ride

Participants were given brief instructions about the test environment and tasks that they would perform. The experiment was divided into four grids. The virtual bicycling course itself was designed to take the participant 10 to 15 minutes to complete. The entire experiment, including the consent process and post-ride questionnaire, lasted approximately 40 minutes.

1.7.6 Simulator Data

Simulator data were collected from the bicycling simulator and *SimObserver* platform during the experiment. A complete data file was generated for each participant for each of the four experimental rides. Files, including video data and all bicycle simulator outputs (e.g., lateral position and velocity) were opened in the *Data Distillery* (Version 1.34) software suite, which provided quantitative outputs (numerical and graphical) in combination with recorded video.

Figure 3.7 shows the *SimObserver* video output in conjunction with numerical data (right side) and graphical representations of data in columns (bottom) opened by *Data Distillery*.

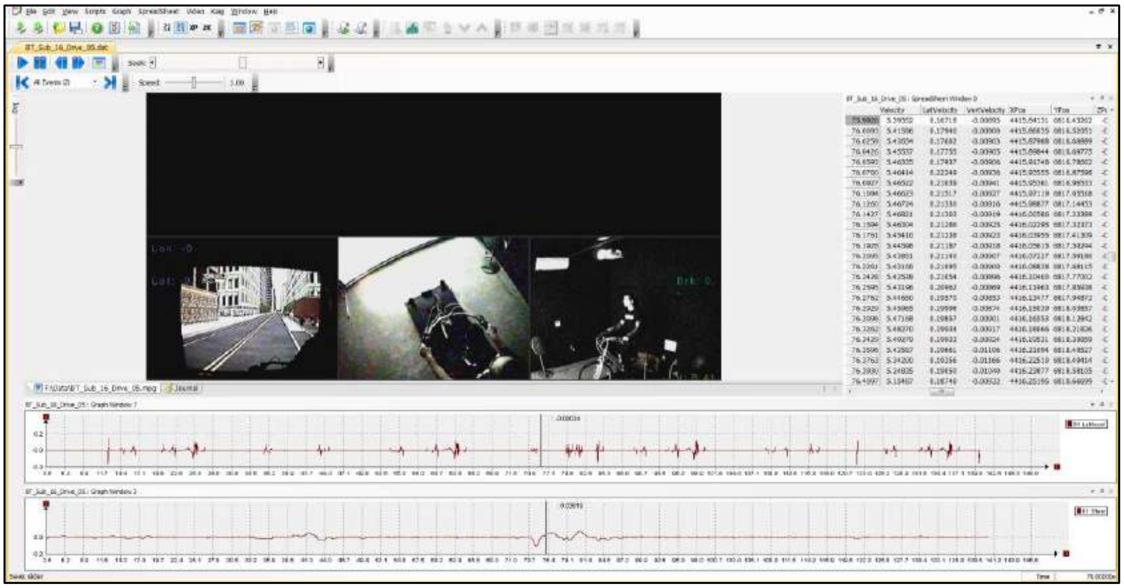

Figure 0.7 Screenshot of *Data Distillery* software interface

Results

This chapter presents the results of the simulator experiment. Section 4.1 describes participant demographics. Section 4.2 investigates bicyclist performance in terms of velocity, lateral position, and acceleration. This chapter also highlights selected events in which individual participants experienced a crash with a truck.

1.8 Participants

Study participants were recruited from the community in and around Corvallis, Oregon.

1.8.1 Summary Statistics

The simulator experiment was successfully completed by 48 participants, including 24 women (M_{age} = 29.71, SD_{age} = 10.03) and 24 men (M_{age} = 28.42, SD_{age} = 11.90). **Error! Reference source not found.** shows participant bicycling habits. Participants most frequently bicycled daily (52.1 percent), to commute to work/school (72.9 percent), and for 10–20 minutes on an average trip (50.0 percent). More than 83 percent of participants had the experience of riding a bicycle in a busy downtown environment.

Table 0.1 Participant bicycling habits

Bicycling Habit	Possible Responses	No. of Participants	Percentage of Participants
Bicycling Frequency	Daily (2–3 times a day)	25	52.1%
	Weekly (2–3 times a week)	10	20.8%
	Monthly (2–3 times a month)	8	16.7%
	Other	5	10.4%
Riding Purpose	Commuting to work/school	35	72.9%
	Recreation	5	10.4%
	Exercise	3	6.3%
	Shopping	2	4.2%
	Other	3	6.3%
Riding Duration	<10 minutes	15	31.3%
	10–20 minutes	24	50.0%
	20–30 minutes	5	10.4%
	>30 minutes	4	8.3%
Downtown Experience	Yes	40	83.3%
	No	8	16.7%

1.8.2 Demographics

Every effort was made to recruit a representative sample of Oregon bicyclists. **Error! Reference source not found.** summarizes the self-reported demographic data of the final sample population.

Table 0.2 Participant demographics

Demographic	Category	No. of Participants	Percentage of Participants
Age	18–24 years	23	47.9%
	25–34 years	16	33.3%
	35–44 years	3	6.3%
	45–54 years	2	4.2%
	55–59 years	2	4.2%
	60–64 years	1	2.1%
	65–74 years	1	2.1%
Gender	Female	24	50.0%
	Male	24	50.0%
Education	High school diploma or GED	2	4.2%
	Some college	22	45.8%
	Trade/vocational school	2	4.2%
	Associate degree	2	4.2%
	Four-year degree	8	16.7%
	Master’s degree	9	18.8%
	PhD degree	3	6.3%
Race	Asian	7	14.6%
	Black or African American	1	2.1%
	White or Caucasian	35	72.9%
	Other	4	8.3%
	Prefer not to answer	1	2.1%
Income	<$25,000	21	43.8%
	$25,000 to <$50,000	5	10.4%
	$50,000 to <$75,000	7	14.6%
	$75,000 to <$100,000	2	4.2%
	$100,000 to <$200,000	6	12.5%
	≥$200,000	3	6.3%
	Prefer not to answer	4	8.3%

1.9 <u>Post-Ride Survey Results</u>

After participants completed the bicycling simulator portion of the experiment, they were asked to complete a short survey regarding the bicycle simulator functionality and their comprehension of different levels of signal indications for right-turn movements. This section presents post-ride survey results.

1.9.1 Bicycle Simulator Functionality

To verify the authenticity of the simulated bicycling task, participants were asked to evaluate subjectively the performance of the bicycle simulator on a scale from 0 (“completely different from the real-world experience”) to 10 (“just like the real-world experience”). Table 4.3 shows the average scores for each category.

Table 0.3 Average scores of authenticity of the bicycling simulator

Handlebar Turning	Pedaling (Acceleration)	Brake (Deceleration)	Urban Environment	Speed Perception	General Level
6.85	6.38	6.38	6.65	6.35	6.92

1.9.2 Signal Indication Comprehension Questions

Each respondent was asked eight multiple-choice questions to determine their comprehension of the CR, CG, SRA, SGA, and FYA signal indications for right-turn movements.

1.9.2.1 CG vs. FYA Signals

Participants were presented the image shown in figure 4.1 and asked two questions:

“A1) Based on the images below, imagine a driver wants to turn right. Consider two displays: flashing yellow arrow and steady circular green ball. Do these mean the same thing to you?

1) Yes - they mean the same thing to me.

2) *No - they have different meanings."*

"A2) Based on the image below, in Oregon, if a driver is turning right and he/she sees the flashing yellow right arrow display, what would be the appropriate response?

1) *Driver can turn right cautiously without stopping.*
2) *Driver can turn right, but first must come to a complete stop and find a gap before turning.*
3) *Driver must stop and wait until they receive a green indication before turning."*

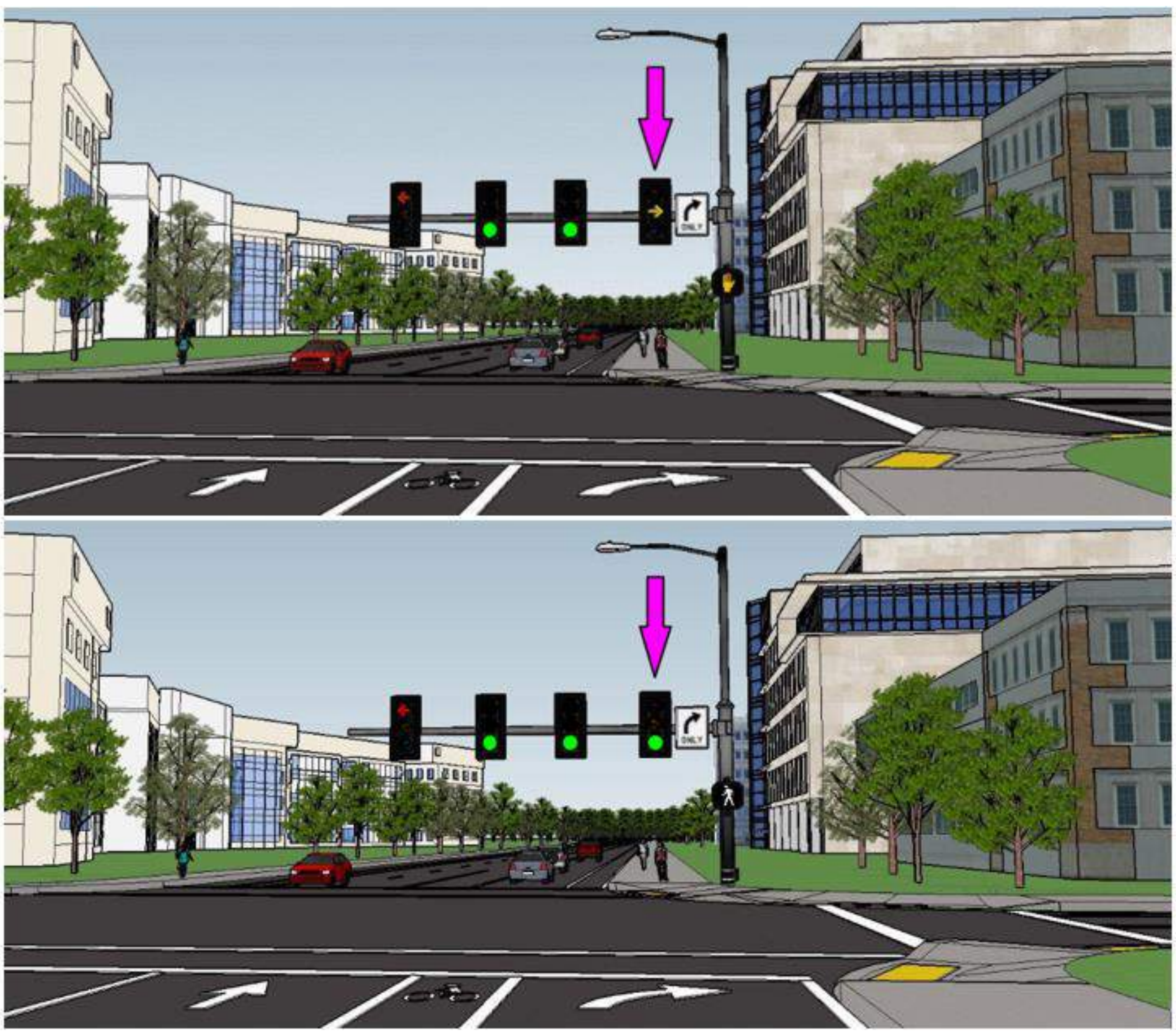

Figure 0.1 Signal indication comprehension. *Top:* FYA. *Bottom:* CG.

Table 4.4 presents participants' responses to these two questions. According to Oregon law, the appropriate response to a FYA for right-turning vehicles is to exhibit caution while turning and yield to pedestrians and cross traffic, while coming to a stop if necessary (Choice 2).

Table 0.4 Participant responses to signal indication comprehension: FYA vs. CG.

Question	Choice 1	Choice 2	Choice 3
A1	11 (22.9%)	37 (77.1%)	N/A
A2	37 (77.1%)	10 (20.8%)	1 (2.1%)

Participants were then presented images showing a conflict between a bicycle and a right-turning vehicle (fig. 4.2) and asked the following questions:

"A3) The gray car in the picture below is going to turn right at the intersection. What do you anticipate will most likely happen in the conflict area (green pavement), given the current signal display for the right-turn lane? (Traffic light is steady green for the bicyclist and yellow right arrow is flashing for the right-turning vehicle).

1) *Vehicle will yield and let the bicyclist pass.*
2) *Vehicle will accelerate and cut off the bicyclist's path.*
3) *Vehicle will cut off the bicyclist's path at its current speed.*
4) *Signal display has no impact on driver's decision.*
5) *Other (please specify)."*

"A4) The gray car in the picture below is going to turn right at the intersection. What do you anticipate will most likely happen in the conflict area (green pavement), given the current signal

display for the right-turn lane? (Traffic light is steady green for both bicyclist and right-turning vehicle).

1) *Vehicle will yield and let the bicyclist pass.*
2) *Vehicle will accelerate and cut off the bicyclist's path.*
3) *Vehicle will cut off the bicyclist's path at its current speed.*
4) *Signal display has no impact on driver's decision.*
5) *Other (please specify)."*

Table 4.5 presents participants' responses to these two questions. Participants who selected Choice 5 ("Other") in response to these questions generally mentioned that they thought the driver would not be able to see the bicyclist in the depicted scenarios.

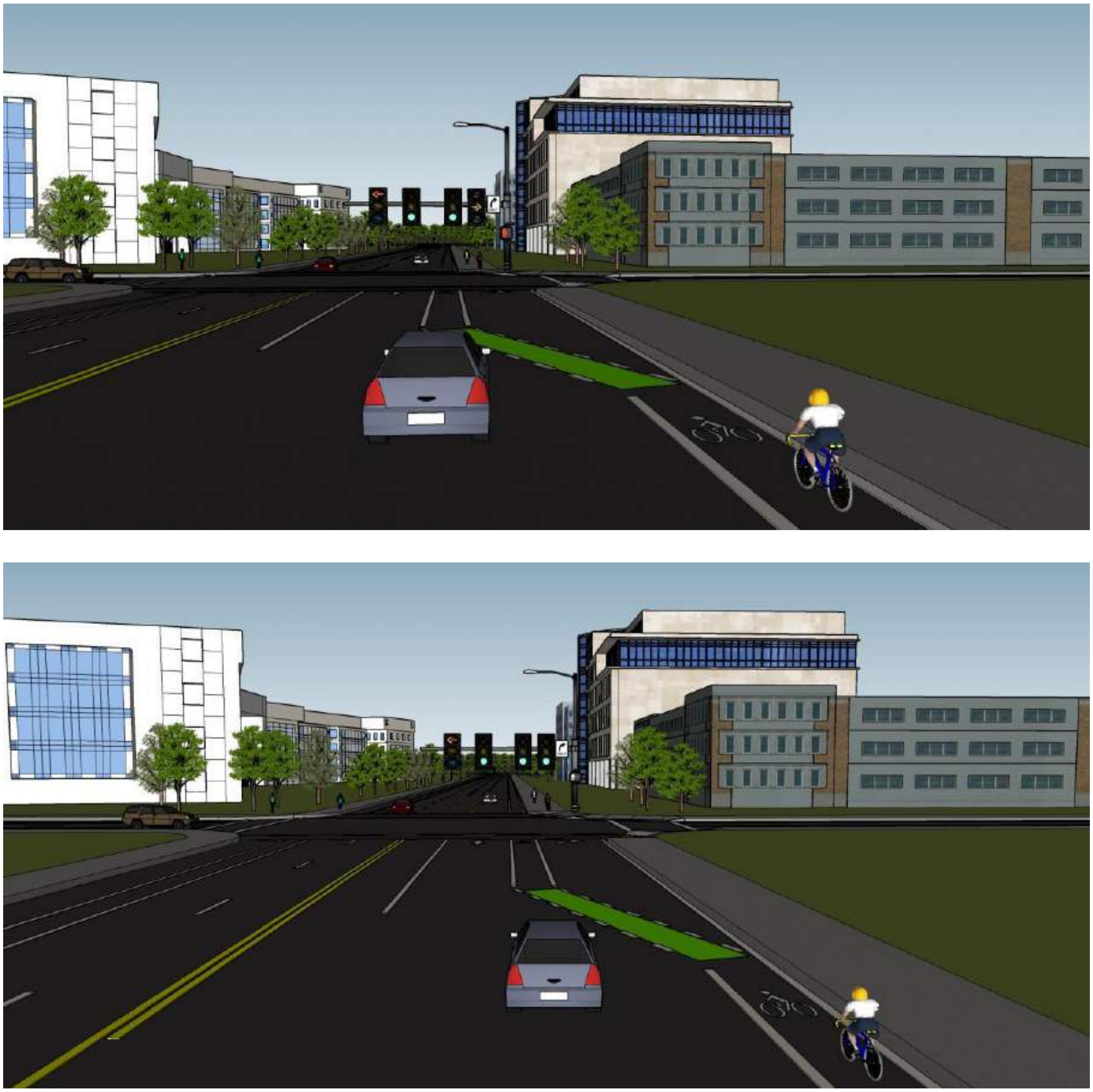

Figure 0.2 Bicycle conflict with right-turning vehicle. *Top:* FYA. *Bottom:* CG.

Table 0.5 Participant responses to right-turning vehicle conflicts: FYA vs. CG.

Question	Choice 1	Choice 2	Choice 3	Choice 4	Choice 5
A3	12 (25.0%)	17 (35.4%)	16 (33.3%)	0 (0.0%)	3 (6.3%)
A4	6 (12.5%)	17 (35.4%)	23 (47.9%)	0 (0.0%)	2 (4.2%)

1.9.2.2 CR vs. SRA Signals

Participants were presented the image shown in figure 4.3 and asked two questions:

"B1) Based on the images below, imagine a driver wants to turn right. Consider the two displays: 1) steady circular red ball, and 2) steady red arrow. Do these displays mean the same thing to you?

1) *Yes - they mean the same thing to me.*
2) *No - they have different meanings."*

"B2) Based on the image below, in Oregon, if a driver is turning right and he/she sees the steady red right arrow display, what would be the appropriate response?

1) *Driver can turn right cautiously without stopping.*
2) *Driver can turn right, but first must come to a complete stop and find a gap before turning.*
3) *Driver must stop and wait until they receive a green indication before turning."*

Table 4.6 presents participants' responses to these two questions. According to Oregon law, the appropriate response to a SRA for right-turning vehicles is to come to a complete stop and then turn if an acceptable gap becomes available after yielding to other traffic and pedestrians, or remain stopped if they fail to find a gap (Choice 2).

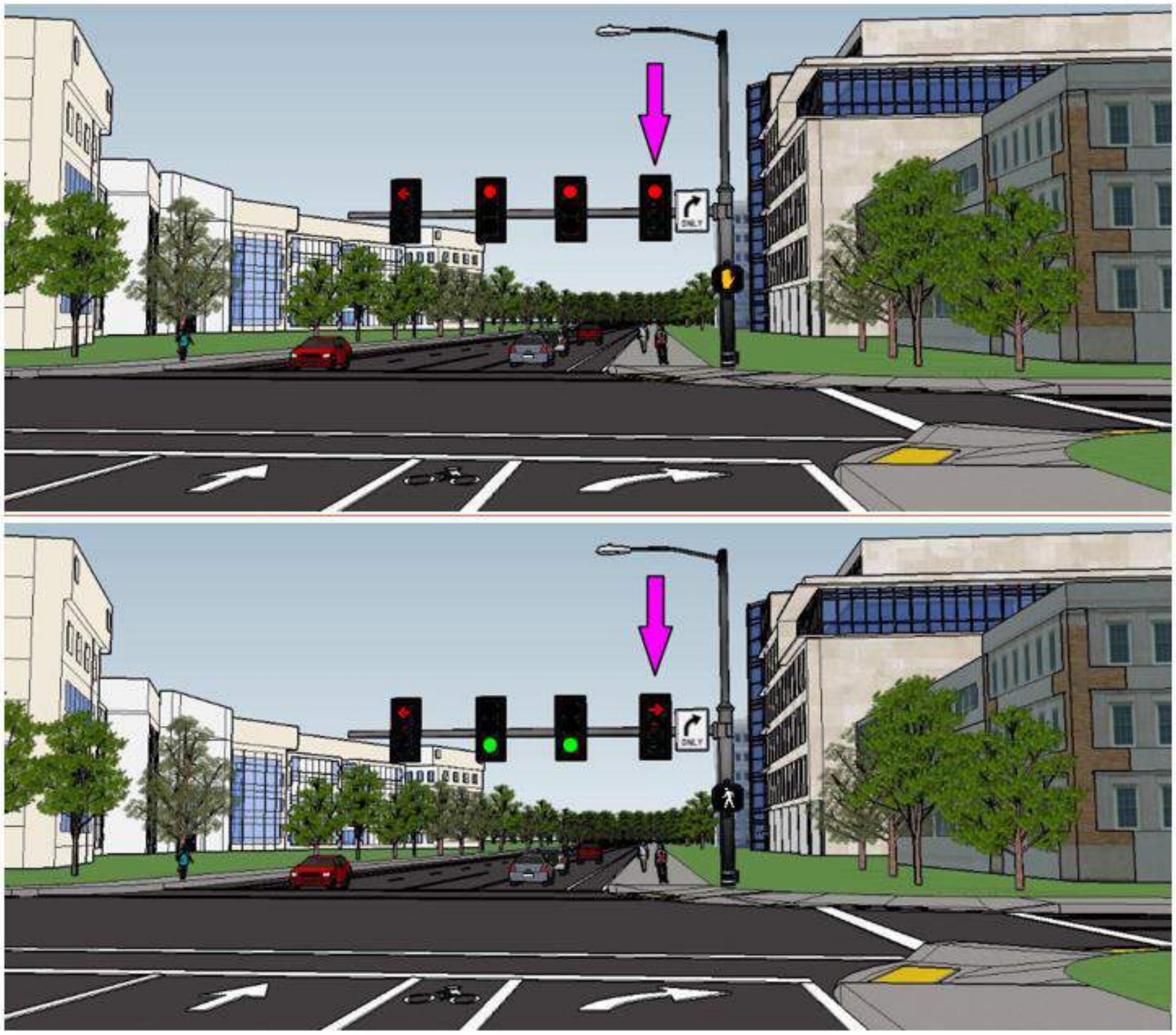

Figure 0.3 Signal indication comprehension. *Top:* CR. *Bottom:* SRA.

Table 0.6 Participant responses to signal indication comprehension: CR vs. SRA.

Question	Choice 1	Choice 2	Choice 3
B1	22 (45.8%)	26 (54.2%)	N/A
B2	2 (4.2%)	16 (33.3%)	30 (62.5%)

They were then presented the images shown in figure 4.4 showing a conflict between a bicycle and a right-turning vehicle and asked the following questions:

"B3) The gray car in the picture below is going to turn right at the intersection. What do you anticipate will most likely happen in the conflict area (green pavement) given the current signal display for right-turn lane? (Traffic light is steady red for both bicyclist and right-turning vehicle).

1) *Vehicle will yield and let the bicyclist pass.*
2) *Vehicle will accelerate and cut off the bicyclist's path.*
3) *Vehicle will cut off the bicyclist's path at its current speed.*
4) *Signal display has no impact on driver's decision.*
5) *Other (please specify)"*

"B4) The gray car in the picture below is going to turn right at the intersection. What do you anticipate will most likely happen in the conflict area (green pavement), given the current signal display for the right-turn lane? (Traffic light is steady green for the bicyclist and red right arrow for the right-turning vehicle).

1) *Vehicle will yield and let the bicyclist pass.*
2) *Vehicle will accelerate and cut off the bicyclist's path.*
3) *Vehicle will cut off the bicyclist's path at its current speed.*
4) *Signal display has no impact on driver's decision.*
5) *Other (please specify)."*

Table 4.7 presents participants' responses to these two questions. Participants who selected Choice 5 ("Other") in response to these questions generally stated that they thought that the driver would not be able to see the bicyclist in the depicted scenarios.

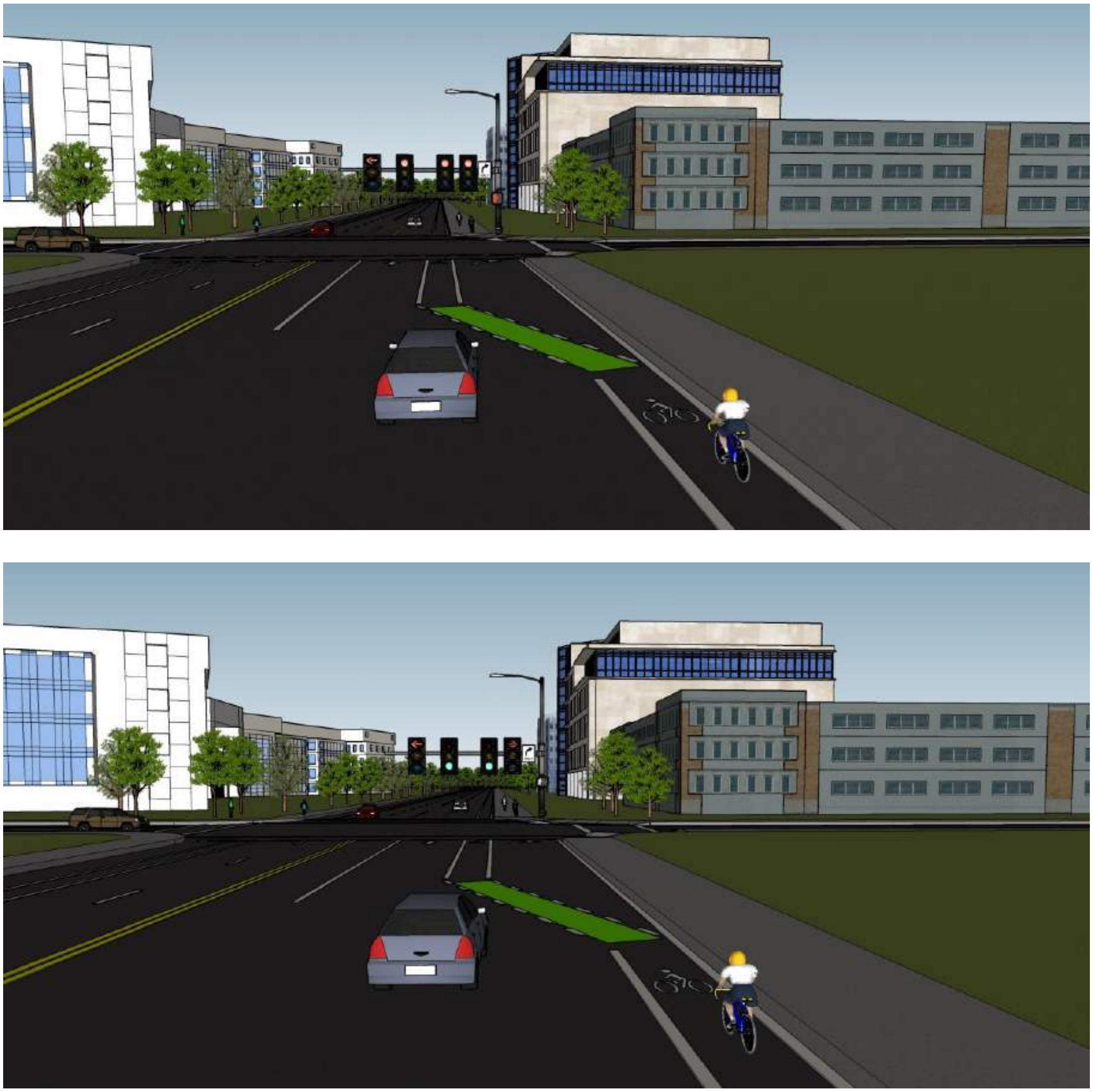

Figure 0.4 Bicycle conflict with right-turning vehicle. *Top:* CR. *Bottom:* SRA.

Table 0.7 Participant responses to right-turning vehicle conflicts: FYA vs. CG.

Question	Choice 1	Choice 2	Choice 3	Choice 4	Choice 5
B3	20 (41.7%)	4 (8.3%)	20 (41.7%)	1 (2.1%)	3 (6.3%)
B4	22 (45.8%)	3 (6.3%)	22 (45.8%)	0 (0.0%)	1 (2.1%)

1.10 Bicyclist Performance

The bicycling simulator collected a large set of data related to the participant bicycling experience, including velocity and lane position, throughout the entire simulation. To observe participant behavior in proximity to a signalized intersection, data were segmented so that the 20 m upstream of the conflict area and the 20-m conflict area were observed. The region 20 m upstream of the conflict area between the bicycle and right-turning vehicle was chosen to encompass the general area where the conflict area, intersection, and signal indications were clearly visible to the bicyclist.

Mixed repeated-measure ANOVA tests were performed with pavement marking and signal indication as within-subject factors and gender as a between-subject factor. Bicyclist velocity and lateral position were analyzed separately as dependent variables. Mauchly's sphericity test was used to confirm sphericity assumptions. A significance level of 0.05 was adopted. Pairwise comparisons of estimated marginal means with Bonferroni adjustment were conducted whenever a significant effect was observed. Effect size was reported by using partial eta squared. IBM SPSS Statistics software version 24 was used for data analysis.

1.10.1 Velocity

Mean (*M*) and standard deviation (*SD*) values for velocity at each level of each independent variable are reported in table 4.4. Bicyclists had the highest mean velocity where no engineering treatment was applied around the conflict area (white lane markings only) and signal indication was CG (women: $M_{Velocity}$ = 5.31 m/s, $SD_{Velocity}$ = 0.83 m/s; men: $M_{Velocity}$ = 5.64 m/s, $SD_{Velocity}$ = 0.95 m/s). Participants encountering a CR while bicycling on a solid green bike lane had the lowest mean velocity (women: $M_{Velocity}$ = 3.96 m/s, $SD_{Velocity}$ = 0.85 m/s; men: $M_{Velocity}$ = 4.63 m/s, $SD_{Velocity}$ = 0.80 m/s).

Table 0.8 Descriptive statistics of velocity (m/s) at each level of each independent variable

Signal Indication	Descriptive Statistics	White Lane Markings		Solid Green	
		Women	**Men**	**Women**	**Men**
CR	*M*	4.67	5.14	3.96	4.63
	(*SD*)	(0.76)	(0.74)	(0.85)	(0.80)
CG	*M*	5.31	5.64	4.45	4.91
	(*SD*)	(0.83)	(0.95)	(0.97)	(0.88)
SRA	*M*	4.70	5.23	4.51	5.10
	(*SD*)	(0.76)	(0.77)	(0.82)	(0.77)
SGA	*M*	4.64	4.96	5.10	5.42
	(SD)	(0.84)	(1.03)	(0.84)	(0.80)
FYA	*M*	4.77	5.17	4.99	5.43
	(*SD*)	(1.03)	(1.12)	(0.82)	(0.91)

Repeated-measure mixed ANOVA tests were used to determine the effects of factors on mean bicyclist velocity. Pairwise comparisons were conducted to find the origin of the difference whenever a significant effect was observed. As shown in table 4.5, pavement marking ($F(1, 46) = 8.179$, $P = 0.006$), signal indication ($F(4, 184) = 16.962$, $P < 0.001$), and gender ($F(1, 46) = 4.618$, $P = 0.037$) had significant main effects on bicyclist velocity. There was also a statistically significant interaction between the combined effects of pavement marking and signal indication on bicyclist velocity ($F(4, 184) = 33.219$, $P < 0.001$). In terms of independent variables, the interaction of pavement marking and signal indication had the highest effect on bicyclist velocity, with about 42 percent of within-subject variance being accounted for by this interaction.

Table 0.9 Mixed repeated-measure ANOVA results on velocity (m/s)

Source	$F(v_1, v_2)$	P	η_p^2
Within-Subject Factors			
Pavement Marking	8.179 (1, 46)*	0.006	0.151
Signal Indication	16.962 (4, 184)*	< 0.001	0.269
Pavement Marking × Signal Indication	33.219 (4, 184)*	< 0.001	0.419
Between-Subject Factors			
Gender	4.618 (1, 46) *	0.037	0.091
Gender × Pavement Marking	0.534 (1, 46)	0.468	0.011
Gender × Signal Indication	1.134 (4, 184)	0.342	0.024
Gender × Pavement Marking × Signal Indication	0.182 (4, 184)	0.948	0.004

Note: F denotes F statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared.
* Statistically significant at 95% confidence interval

By using Bonferroni corrected post-hoc tests for pairwise comparison of the main effect of pavement marking, it was found that regardless of the type of signal indication and bicyclist gender, participants biked more slowly on solid green bike lanes ($P = 0.006$). Pairwise comparisons for the main effect of signal indication also showed that regardless of the type of pavement marking and gender, participants encountering a CR indication biked significantly more slowly than bicyclists encountering all other signal indications ($P < 0.001$ for all pairwise comparisons). No significant difference was observed for other levels of signal indication. Finally, pairwise comparison for the main effect of gender showed that regardless of pavement marking or signal indication, women biked significantly more slowly than men ($P = 0.006$).

Two-way interactions were considered in the pairwise comparison for pavement marking and signal indication. Figure 4.4 plots the estimated marginal mean velocity at each level of pavement marking and signal indication. Pairwise comparisons showed that regardless of gender, participants biked significantly more quickly with white lane markings than with solid green for CR ($P < 0.001$), CG ($P < 0.001$), and SRA ($P = 0.021$). Participants biked significantly more slowly with white lane markings than with solid green for SGA ($P < 0.001$) and FYA ($P = 0.041$).

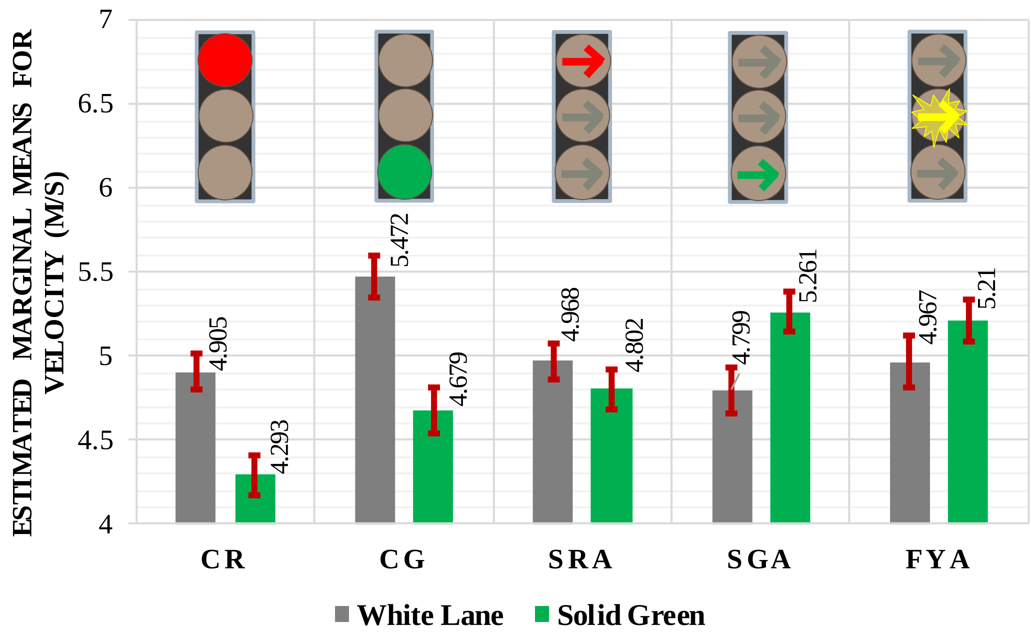

Figure 0.5 Statistically significant two-way interactions on velocity, by ANOVA

Considering the application of PPRT phasing, figure 4.6 shows velocity distribution against signal indication disaggregated by pavement marking type. Pairwise comparison results showed that with the white lane marking in place, there was no statistically significant difference between CR and SRA ($P = 0.325$); however, participants encountering a CG had a significantly higher velocity than those encountering a FYA ($P < 0.001$). With solid green pavement markings in place, participants had a significantly higher velocity for SRA than for CR ($P < 0.001$) and for the FYA in comparison to the CG ($P < 0.001$).

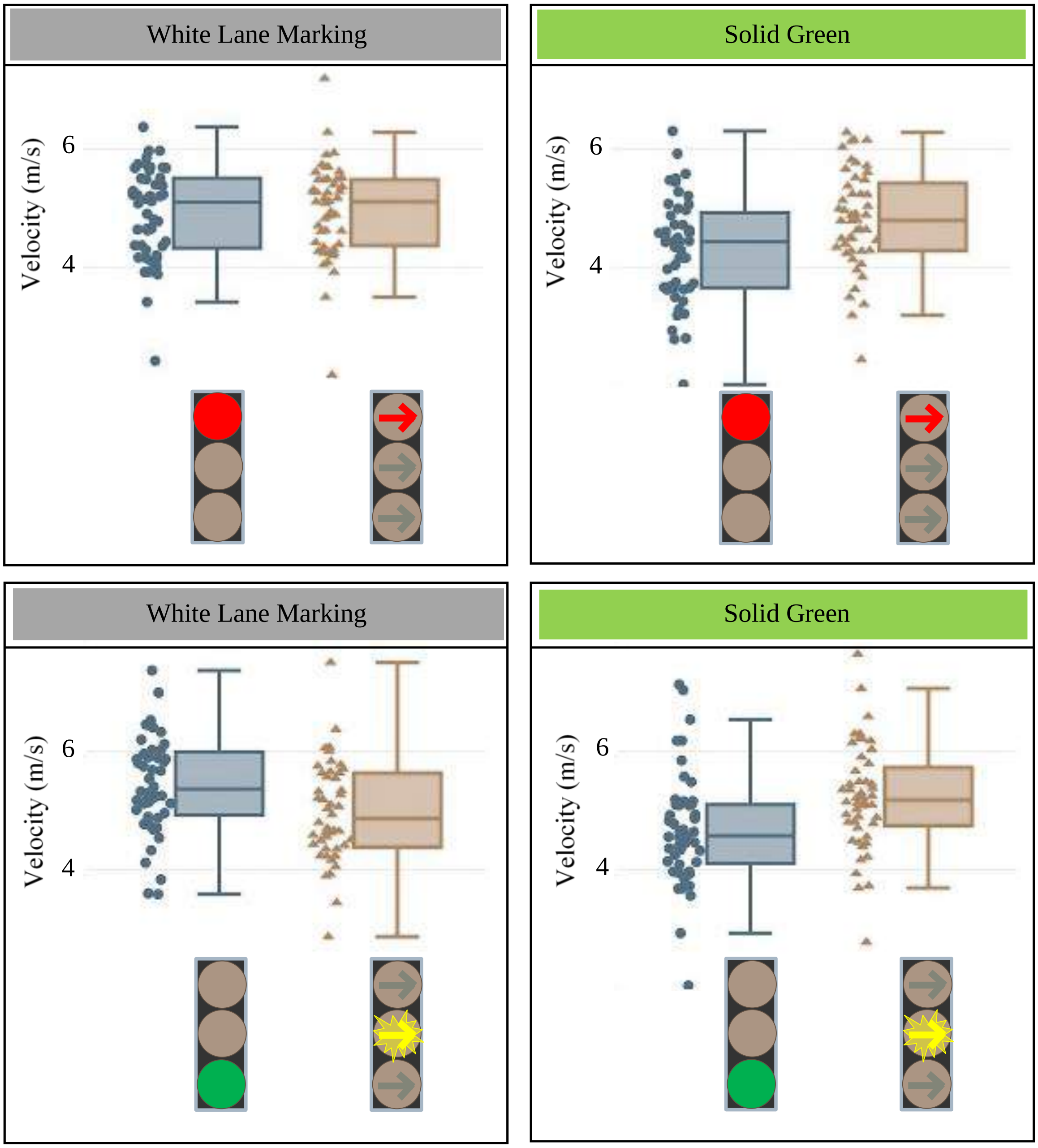

Figure 0.6 Effects of application of PPRT phasing on velocity

1.10.2 Lateral Position

Descriptive statistics of the lateral position for each independent variable level are reported in table 4.6. The right edge of the bike lane was defined as 0 m, making the left edge 1.83 m. Women had the least divergence from the right edge of the bike lane when no colored pavement marking was used (only white lane markings) and the signal indication was SGA ($M_{Lateral}$ = 0.58 m, $SD_{Lateral}$ = 0.14 m). Men had the least divergence from the right edge of the bike lane under two different conditions: 1) when white lane markings were used in conjunction with SGA ($M_{Lateral}$ = 0.60 m, $SD_{Lateral}$ = 0.18 m), and 2) when solid green was used in conjunction with CR ($M_{Lateral}$ = 0.60 m, $SD_{Lateral}$ = 0.14 m). Participants of both genders encountering a CR while in a bike lane with white lane markings had the most divergence from the right edge of the bike lane (women: $M_{Lateral}$ = 0.81 m, $SD_{Lateral}$ = 0.21 m; men: $M_{Lateral}$ = 0.75 m, $SD_{Lateral}$ = 0.17 m).

Table 0.10 Descriptive statistics of lateral position (m) at the independent variable level

Signal Indication	Descriptive Statistics	White Lane Markings		Solid Green	
		Women	Men	Women	Men
CR	*M*	0.67	0.64	0.59	0.60
	(*SD*)	(0.18)	(0.14)	(0.15)	(0.14)
CG	*M*	0.81	0.75	0.62	0.59
	(*SD*)	(0.21)	(0.17)	(0.16)	(0.15)
SRA	*M*	0.65	0.64	0.69	0.63
	(*SD*)	(0.16)	(0.15)	(0.18)	(0.11)
SGA	*M*	0.58	0.60	0.68	0.63
	(*SD*)	(0.14)	(0.18)	(0.30)	(0.14)
FYA	*M*	0.70	0.71	0.70	0.65
	(*SD*)	(0.18)	(0.23)	(0.22)	(0.16)

Repeated-measure mixed ANOVA tests were used to determine the effects of factors on the mean lateral position of bicyclists, with pairwise comparisons used to find the origin of any significant difference. As shown in table 4.7, pavement marking ($F(1, 46) = 11.953$, $P = 0.001$) and signal indication ($F(4, 184) = 8.700$, $P < 0.001$) had significant main effects on the lateral position of the bicyclist. There was a statistically significant interaction between the combined effects of pavement marking and signal indication on lateral position ($F(4, 184) = 11.451$, $P < 0.001$). In terms of independent variables, pavement marking had the highest effect on lateral position and accounted for about 21 percent of within-subject variance.

Table 0.11 Mixed repeated-measures ANOVA results on lateral position

Source	***F*(v_1, v_2)**	***P***	η_p^2
Within-Subject Factors			
Pavement Marking	11.953 (1, 46)*	0.001	0.206
Signal Indication	8.700 (4, 184)*	< 0.001	0.159
Pavement Marking × Signal Indication	11.451 (4, 184)*	< 0.001	0.199
Between-Subject Factors			
Gender	0.383 (1, 46)	0.539	0.008
Gender × Pavement Marking	0.685 (1, 46)	0.412	0.015
Gender × Signal Indication	0.429 (4, 184)	0.787	0.009
Gender × Pavement Marking × Signal Indication	1.027 (4, 184)	0.395	0.022

Note: *F* denotes *F* statistic; v_1 and v_2 denote degrees of freedom; η_p^2 denotes partial eta squared.
* Statistically significant at 95% confidence interval

Results of Bonferroni-corrected post-hoc tests, used for pairwise comparison of the main effect of pavement marking, showed that regardless of the type of signal indication and bicyclist gender, participants had a significantly lower divergence from the right edge on solid green bike lanes ($P = 0.001$). Pairwise comparisons for the main effect of signal indication showed that regardless of the type of pavement marking and gender, participants encountering a CR or SRA indication had a significantly lower divergence than those encountering a CG ($P < 0.001$ for CR and $P = 0.001$ for SRA) or FYA indication ($P = 0.009$ for CR and $P = 0.003$ for SRA). No significant difference was observed for other levels of signal indication.

Two-way interactions were considered in the pairwise comparison for pavement marking and signal indication. Figure 4.6 plots the estimated marginal means of lateral position at each level of pavement marking and signal indication. Regardless of gender, participants had a significantly higher divergence in white lane markings than in solid green pavement for CR (*P* = 0.011) and CG (*P* < 0.001). Participants had a significantly lower divergence in white lane markings than in solid green pavement for SGA (*P* = 0.044) and FYA (*P* = 0.041).

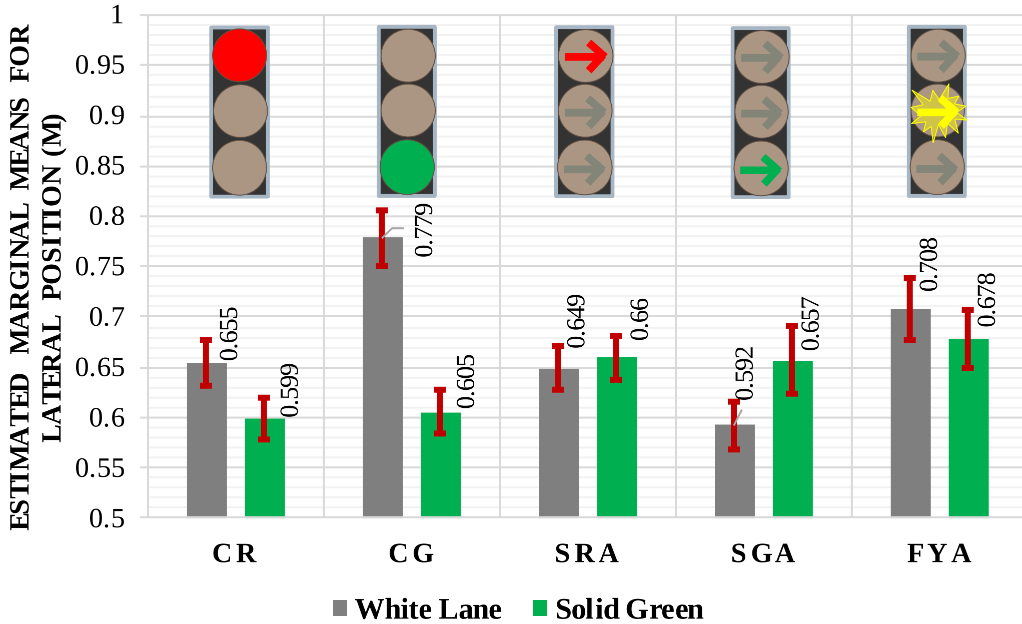

Figure 0.7 Statistically significant two-way interactions on lateral position, by ANOVA

Regarding the application of PPRT phasing, figure 4.8 shows the distribution of the lateral position against signal indication divided by type of pavement marking. Pairwise comparison results showed that with white lane markings in place, there was no statistically significant difference between CR and SRA (*P* = 0.694), but participants encountering the CG had a significantly higher divergence than those encountering the FYA (*P* = 0.033). With solid green pavement markings in place, participants had a significantly higher divergence for SRA than for CR (*P* = 0.003) and for FYA than for CG (*P* = 0.003).

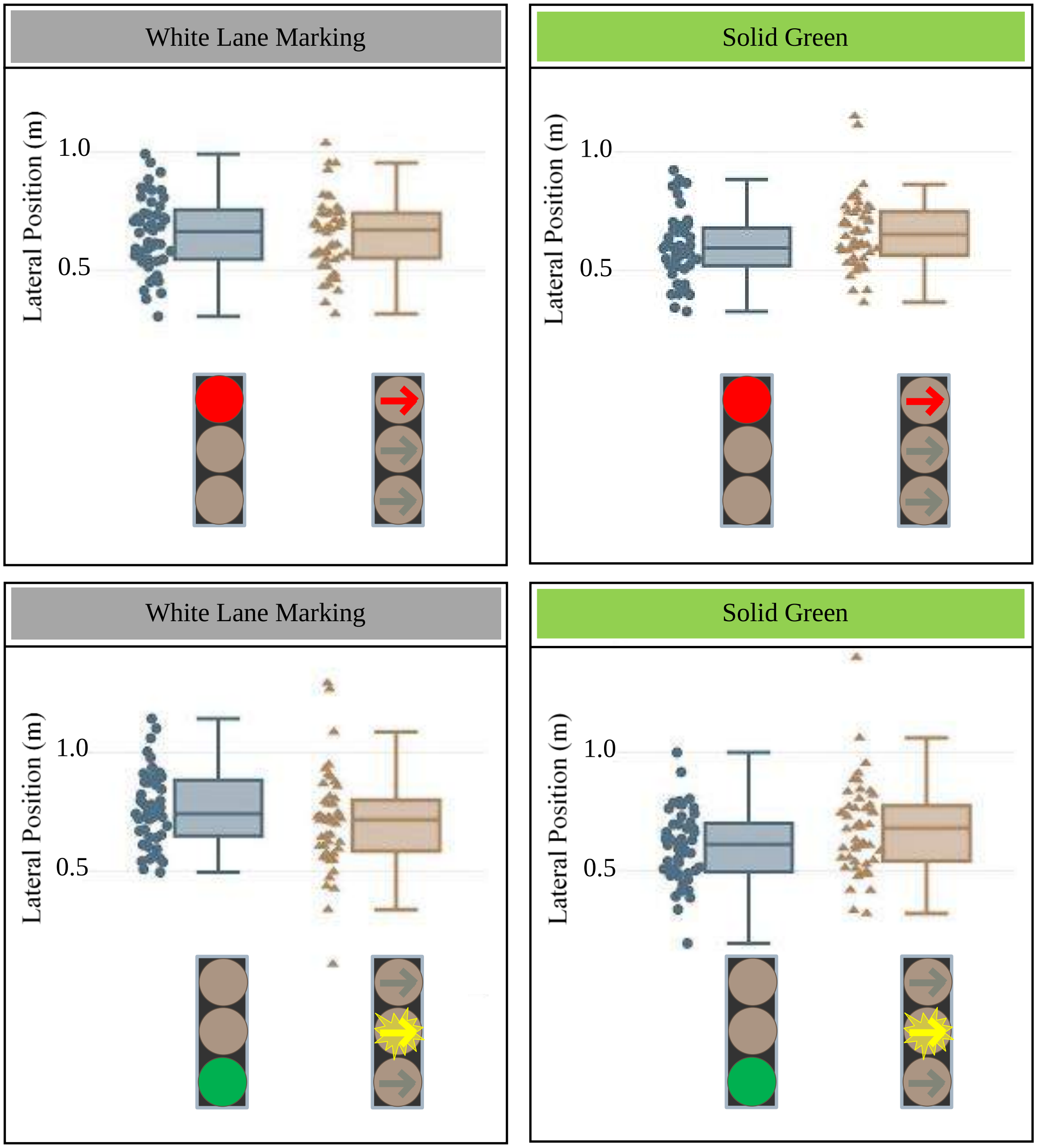

Figure 0.8 PPRT phasing application effects on lateral position

Conclusions

This chapter presents study conclusions related to the interaction of bikes and right-turning vehicles at the approach to a signalized intersection. The first section summarizes the major findings of the experiment. The following sections discuss the limitations of this study and opportunities for future research.

1.11 Findings

The results of this study demonstrated a consistent narrative related to how bicyclists interact with right-turning vehicles at the approaches to signalized intersections, and how different levels of engineering treatments are effective. Overall, the results showed that the application of PPRT does affect bicyclist performance, and this effect varies on the basis of the pavement marking employed. The primary findings of this study are as follows:

- Most participants did not have a correct comprehension of PPRT phasing and the associated ROW.
- When an SRA indication was used instead of a CR, with no colored pavement marking (white lane marking only), no difference was observed in bicyclist behavior. However, when solid green pavement markings were applied to the conflict area, bicyclists tended to bike at faster speeds and to divert more toward the travel lane.
- When an FYA indication was used instead of a CG, with no colored pavement marking (white lane marking only), bicyclists biked more slowly and stayed farther away from the travel lane. However, with a solid green pavement marking applied to the conflict area, the bicyclists biked more quickly and diverted more toward the travel lane.
- Regardless of signal indication and pavement marking, male bicyclists had a significantly higher velocity than female bicyclists during a conflict with right-turning vehicles.

Table 5.1 summarizes the findings from the bicycling simulation experiment.

Table 0.1 Summary of findings from bicycling simulation experiment

Pavement Markings	**CR vs. SRA**	**CG vs. FYA**
White lane markings with no supplemental colored pavement	$V^{*}_{CR} \equiv V_{SRA}$	$V_{CG} > V_{FYA}$
	$L^{*}_{CR} \equiv L_{SRA}$	$L_{CG} > L_{FYA}$
White lane markings with solid green	$V_{CR} < V_{SRA}$	$V_{CG} < V_{FYA}$
	$L_{CR} < L_{SRA}$	$L_{CG} < L_{FYA}$

* V stands for Velocity. L stands for Lateral Position.

1.12 Recommendations

The findings of the present study suggest that the influence of PPRT phasing on bicyclist performance is contingent upon the type of pavement marking. Figure 5.1 shows changes in bicyclist behavior as the result of the concurrent change in signal indication or pavement marking. When the solid green pavement marking was used, exchanging typical signal indications with PPRT phasing (CR with SRA in Case B, and CG with FYA in Case D) negatively affected conflicts between bicyclists and right-turning vehicles by increasing the velocity of bicyclists and causing them to move closer to the travel lane (increase in lateral position). When no colored pavement marking was used, replacing a CR with an SRA (Case A) had no effect on bicyclist behavior, but replacing a CG with an FYA (Case C) improved bicyclist safety by decreasing the velocity of bicyclists and causing them to move farther away from the travel lane (decrease in lateral position).

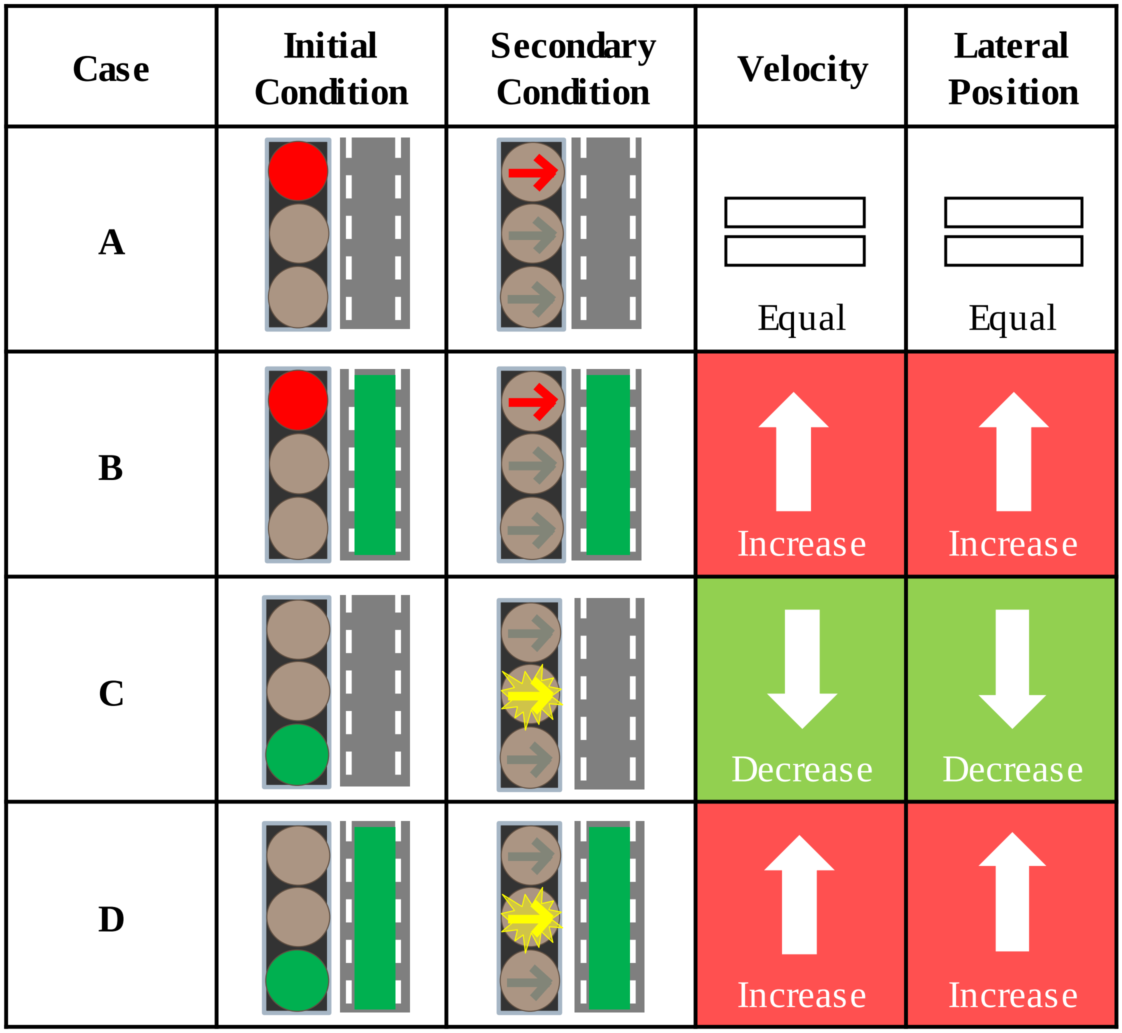

Figure 0.1 Effects of PPRT phasing and pavement markings on bicyclist behavior

1.13 <u>Limitations</u>

- A basic limitation of within-subject design is the possibility of fatigue and carryover effects, which can cause a participant's performance to degrade over the course of the experiment as s/he becomes tired or bored. The order of the scenarios was partially randomized, and the test drives were kept relatively brief, to minimize these effects.

- The visual display of the bicycle simulator used in this study did not provide a peripheral field of view for participants. While peripheral vision was limited, a small window was placed on the top left corner of the screen, providing a rear view for bicyclists.
- Resource and time constraints of the project limited the number and levels of variables that could be evaluated. In particular, the right-turning conflict was only analyzed with a 2.5-second cut-in time gap, and only conventional bike lanes were modeled.
- Although all efforts were made to recruit a sample of bicyclists similar to the bicyclist population in the state of Oregon, the final sample was slightly skewed toward younger and more educated riders.

1.14 Future Work

Additional research is needed to explore further the critical safety issue of interactions between bicycles and right-turning vehicles. The following are potential research threads that would augment this study and expand the topic of how bicyclists interact with right-turning vehicles as they approach signalized intersections.

- This research studied signal indications and pavement markings as independent variables for bike and right-turning vehicle interactions. Many other variables could be considered. For example, shorter cut-in time gaps (e.g., 1-second) could provide higher rates of crashes and near-miss events. Alternative bike lane configurations (e.g., buffered or contra-flow bike lanes) could be modeled in a virtual environment to quantitatively compare the effectiveness of different design practices.
- Providing a display with a larger viewing angle would enable bicyclist behavior to be monitored from the time that the right-turning vehicle was behind the bicyclist until it weaved across the bike lane in front of the bicyclist.

- Incorporating a wider range of vehicle types, traffic volumes, and operating speeds would expand the scope of the study.
- Using an instrumented bicycle experiment in an urban area could contribute to validation of the study results.

References

Babu, Sabarish V., Grechkin, Timofey Y., Chihak, Benjamin, Ziemer, Christine, Kearney, Joseph K., Cremer, James F., and Jodie M. Plumert. 2011. "An immersive virtual peer for studying social influences on child cyclists' road-crossing behavior." *Visualization and Computer Graphics, IEEE Transactions*, 17(1): 14-25.

Bui, Bill, Cameron, Max, and Foong Chee Wai. 1991. "Effect of right turn phases at signalized intersections. Part 1 – safety performance." *Report No. 20*. MONASH University Accident Research Centre, Clayton, Australia.

Caro, Stéphane, and Silvia Bernardi. 2015. "The role of various sensory cues in self-speed perception: a bicycle riding simulator preliminary study." *Paper presented at the Driving Simulation Conference*, Tubingen, Allemagne, 16–18 Sept. 2015.

Chihak, Benjamin J., Plumert, Jodie M., Ziemer, Christine J., Babu, Sabarish, Grechkin, Timofey, Cremer, James F., and Joseph K. Kearney. 2010. "Synchronizing self and object movement: how child and adult cyclists intercept moving gaps in a virtual environment." *Journal of Experimental Psychology: Human Perception and Performance*, 36(6), 1535-1552. doi:10.1037/a0020560.

Deutsch, Judith, Myslinski, Mary Jane, Ranky, Richard, Sivak, Mark, Mavroidis, Constantinos, and Jeffrey Lewis. 2012. "Fitness improved for individuals post-stroke after virtual reality augmented cycling training." *Proceedings of the 9th International Conference on Disability, Virtual Reality, and Associated Technologies*, Laval, France, 10–12 Sept. 2012.

ElectronicSports. 2008. Online. Accessed 4/22/2016. http://electronicsports.com/ESFlashSite/

Fatality Analysis Reporting System (FARS). 2017. "FARS data tables: summary". Online. Accessed 1/18/2018. http://www-fars.nhtsa.dot.gov/Main/index.aspx

Federal Highway Administration (FHWA). 2009. *Manual on Uniform Control Devices*. U.S. Department of Transportation, Washington, D.C.

Federal Highway Administration (FHWA). 2015. "Signs and signals: right turn on red restrictions." U.S. Department of Transportation, Washington, D.C. Online. Accessed 3/1/2018. http://safety.fhwa.dot.gov/saferjourney1/library/countermeasures/41.htm

Fisher, Donald L., Rizzo, Matthew, Caird, Jeffrey, and John D. Lee, eds., 2011. *Handbook of Driving Simulation for Engineering, Medicine, and Psychology*. CRC Press, Boca Raton, Florida.

Furth, Peter G., Koonce, Peter, Yu, Miao, Peng, Fei, and Michael Littman. 2014. "Mitigating the right turn conflict using protected-yet-concurrent phasing for cycle track and pedestrian crossings." *Transportation Research Record: Journal of the Transportation Research Board*, 2438: 81-88.

Grechkin, Timofey Y., Chihak, Benjamin J., Cremer, James F., Kearney, Joseph K., and Jodie M. Plumert. 2013. "Perceiving and acting on complex affordances: how children and adults bicycle across two lanes of opposing traffic." *Journal of Experimental Psychology: Human Perception and Performance*, 39(1): 23-36. doi:10.1037/a0029716.

He, Qichang, Fan, Xiumin, and Dengzhe Ma. 2005. "Full bicycle dynamic model for interactive bicycle simulator." *Journal of Computing and Information Science in Engineering*, 5(4): 373-380.

Hurwitz, David, Jannat, Mafruhatul, Warner, Jennifer, Monsere, Christopher, and Ali, R. 2015. "Towards effective design treatment for right turns at intersections with bicycle traffic." *Report No. FHWA-OR-RD-16-06*, Oregon Department of Transportation, Salem, Oregon.

Hwan, Jeong S., Jun, Piao Y., Suk, Chong W., Yook, Kim Y., Min, Lee S., Kyu, Kwon, T., Un, Hong C., and Gyun, Kim N. 2006. "The development of a new training system for improving equilibrium sense using a virtual bicycle simulator". *Proceedings of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, 3: 2567-2570.

Jannat, Mafruhatul. 2014. "Right-hook crash causality at signalized intersections." Dissertation, Oregon State University, Corvallis, Oregon.

Kwon, Dong-Soo, Yang, Gi-Hun, Lee, Chong-Won, Shin, Jae-Cheol, Park, Youngjin, Jung, Byungbo, Lee, Doo Yong, Lee, Kyungno, Han, Soon-Hung, Yoo, Byoung-Hyun, Wohn, Kwang-Yun, and Ahn, Jung-Hyun. 2001. "KAIST interactive bicycle simulator". *Proceedings of the 2001 IEEE International Conference*. 3: 2313-2318.

Liu, Wei-Chung, Jeng, Ming-Chang, Hwang, Jiun-Ren, Doong, Ji-Liang, Lin, Chih-Yung, and Lai, Ching-Huei. 2012. "The response patterns of young bicyclists to a right-turning motorcycle: a simulator study." *Perceptual and Motor Skills*, 115(2): 385-402. doi:10.2466/22.25.27.PMS.115.5.385-402

Moore, K. 2008. "Early history of flight simulation". Online. Accessed 4/22/2016. https://www.simulationinformation.com/education/early-history-flight-simulation

National Association of City Transportation Officials (NACTO). 2011. "Urban bikeway design guide." Online. Accessed 3/30/2018. https://nacto.org/publication/urban-bikeway-design-guide/

National Highway Traffic Safety Administration (NHTSA). 2010. "Traffic safety facts 2010: A compilation of motor vehicle crash data from the Fatality Analysis Reporting System and the General Estimates System." *Publication DOT HS 811 659*. U.S. Department of Transportation, Washington, D.C. Online. Accessed 3/1/2018.

http://www-nrd.nhtsa.dot.gov/Pubs/811659.pdf.

National Highway Traffic Safety Administration (NHTSA). 2017. "Bicyclists and other cyclists: 2015 data." U.S. Department of Transportation, Washington, D.C. Online. Accessed 3/1/2018. https://crashstats.nhtsa.dot.gov/Api/Public/Publication/812382

Oregon Department of Transportation (ODOT). 2015. "Traffic signal policy and guidelines". Oregon Department of Transportation, Salem, OR. Online. http://www.oregon.gov/ODOT/Engineering/Documents_TrafficStandards/Traffic-Signal-Policy-Guidelines.pdf

Oregon Department of Transportation (ODOT). 2017. "2015 Oregon traffic crash summary". Oregon Department of Transportation, Salem, OR. Online. Accessed 3/1/2018. http://www.oregon.gov/ODOT/Data/Documents/Crash_Summary_2015.pdf

Owens, D. A., and R. A. Tyrrell. 1999. Effects of luminance, blur, and age on nighttime visual guidance: A test of the selective degradation hypothesis. *Journal of Experimental Psychology: Applied*, Vol. 5, No. 2, 1999, pp. 115-128.

Plumert, Jodie M., Kearney, Joseph K., and James F. Cremer. 2004. "Children's perception of gap affordances: bicycling across traffic-filled intersections in an immersive virtual environment". *Child Development*, 75(4): 1243-1253. doi:10.1111/j.1467-8624.2004.00736.x

Plumert, Jodie, Kearney, Joseph, and James F. Cremer. 2007a. "How does traffic density influence cyclists' gap choices?" *Proceedings of the 2007 International Conference on Road Safety and Simulation (RSS2007)*, Rome, Nov. 2007.

Plumert, Jodie M., Kearney, Joseph K., and James F. Cremer. 2007b. "Children's road crossing: a window into perceptual-motor development." *Current Directions in Psychological Science*, 16(5): 255-258. doi:10.1111/j.1467-8721.2007.00515.x

Plumert, Jodie M., Kearney, Joseph K., Cremer, James F., Recker, Kara M., and Jonathan Strutt. 2011. "Changes in children's perception-action tuning over short time scales: bicycling across traffic-filled intersections in a virtual environment." *Journal of Experimental Child Psychology*, 108(2): 322-337. doi:10.1016/j.jecp.2010.07.005

Portland Bureau of Transportation (PBOT). 2010. "Portland Bicycle Plan for 2030". Portland Bureau of Transportation, Portland, OR. Online. Accessed 8/18/2016. https://www.portlandoregon.gov/transportation/44597

Ranky, Richard, Sivak, Mark, Lewis, Jeffrey, Gade, Venkata, Deutsch, Judith E., and Constantinos Mavroidis. 2010. "VRACK—virtual reality augmented cycling kit: design and validation". *Proceedings of the IEEE Virtual Reality Conference (VR 2010)*, Waltham, MA, 20–24 Mar. 2010.

Seattle Department of Transportation (SDOT). 2007. "Seattle Bike Master Plan". Seattle Department of Transportation, Seattle, WA. Online. Accessed 2/20/2015. http://www.seattle.gov/transportation/docs/bmp/final/Chapter2.pdf

Stevens, Erin, Plumert, Jodie M., Cremer, Joseph F., and James K. Kearney. 2013. "Preadolescent temperament and risky behavior: Bicycling across traffic-filled intersections in a virtual environment." *Journal of Pediatric Psychology*, 38(3): 285-295. doi:10.1093/jpepsy/jss116

U.S. Department of Transportation (USDOT). 2015. *National Cooperative Highway Research Program: Signal Timing Manual Second Edition*. U.S. Department of Transportation, Washington, D.C.

Vogt, Tobias, Herpers, Rainer, Askew, Christopher D., Scherfgen, David, Steuder, Heiko K., and Stefan Schneider. 2015. "Effects of exercise in immersive virtual environments on cortical neural oscillations and mental state." *Neural Plasticity*, Article ID 523250, 9 pages. doi:10.1155/2015/523250.

Watson, Grieg, and Tom Swensen. 2006. "Effects of altering pedal cadence on cycling time-trial performance." *International Journal of Sports Medicine*, 27(4): 296-300.