AN EXAMINATION OF THE IMPACT OF COMMERCIAL PARKING UTILIZATION ON CYCLIST BEHAVIOR IN URBAN ENVIRONMENTS

FINAL PROJECT REPORT

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16. Abstract

There is little research on the behavioral interaction between bicycle lanes and commercial vehicle loading zones in the United States. These interactions are important to understand, to preempt increasing conflicts between truckers and bicyclists. In this study, a bicycling simulator experiment examined bicycle and truck interactions. The experiment was successfully completed by 48 participants. The bicycling simulator collected data regarding a participant's velocity, lane position, and acceleration. Three independent variables were included in this experiment: pavement marking (white lane markings with no supplemental pavement color (white lane markings), white lane markings with solid green color applied to conflict areas (solid green), and white lane markings with dashed green color applied to conflict areas (dashed green)); signage (with and without a truck warning sign); and truck maneuver (no truck in the load zone, truck parked in the load zone, and truck pulling out of the load zone).

The following bike-truck interactions were observed from the simulation. Bicyclists had the highest mean velocity when there was a white lane marking and no warning sign, and had the lowest mean velocity when there was a solid green pavement, no warning sign, and an exiting truck. Of the three independent variables, truck maneuvering had the greatest impact by decreasing mean bicyclist velocity. Bicyclists had the least lateral divergence when there was a white lane marking, a warning sign, and no truck. Of the three independent variables, truck maneuvering (parked and exiting) increased lateral movements, while solid green pavement markings decreased lateral variability. Bicyclists had the highest acceleration when there was a white lane marking, no truck, and a warning sign. Of the three independent variables, truck maneuvering had the greatest impact by increasing bicyclist acceleration. The results showed that truck presence does have an effect on bicyclist's performance, and this effect varies on the basis of the engineering and design treatments employed. The findings of the current study showed that when a truck is present in a loading zone, solid green pavement causes bicyclists to have a lower velocity and lower divergence from the right edge of the bike lane, and employment of a warning sign causes a higher divergence from the right edge of the bike lane.

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List of Abbreviations

CVLZ: Commercial Vehicle Loading Zone
FARS: Fatality Analysis Reporting System
FHWA: Federal Highway Administration
NACTO: National Association of City Transportation Officials
NHTSA: National Highway Traffic Safety Administration
OSU: Oregon State University
PBOT: Portland Bureau of Transportation
SDOT: Seattle Department of Transportation
SFMTA: San Francisco Municipal Transportation Agency

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1. Introduction

According to the U.S. Census Bureau, the number of cyclists commuting to work in the United States grew by 60 percent between 2000 and 2012 (U.S Census Bureau 2014). As population growth forces city leadership to reevaluate land use and diversify modes of transit to relieve traffic congestion, urban policy makers and planners are recognizing the importance of investing in bicycle infrastructure (Rowangould and& Tayarani 2016). However, urban areas are also linked to an increase in the number of commercial vehicles travelling and delivering goods alongside cyclists. Statistics from the U.S. Department of Transportation Federal Highway Administration (FHWA) portray this growth. Between 2010 and 2014, the number of registered trucks and truck-tractors in the U.S. increased by 27,118,040 (FHWA 2011, 2014). PacTrans and the Seattle Department of Transportation (SDOT) conducted a study entitled “An Evaluation of Bicycle Safety Impacts of Seattle’s Commercial Vehicle Load Zones” to investigate how commercial vehicle loading zones (CVLZ) affect cyclist safety on the road (Butrina et al., 2016). The study concluded that better assessing the needs of a loading/unloading truck at the curb in tandem with understanding bicyclist road behavior through simulation will improve cyclist safety around CVLZs.

The Manual on Uniform Traffic Control Devices (MUTCD) does not include a national standard for CVLZs (2009). Therefore, cities across the United States have various rules and regulations for these zones, but they generally include a paid permit and signage to indicate the constraints within the loading zone. Figure 1.1 shows an example of CVLZ signage in Seattle, Washington.

Figure 1.1 SDOT's Commercial vehicle loading zones signage (Source SDOT 2015)

There is little research on the compromised space between bicycle lanes and CVLZs in the United States. However, observations of bike lanes adjacent to CVLZs in Seattle have demonstrated the conflicts between the two modes. Figures 1.2 and 1.3 shows a range of commercial vehicle classes parked in CVLZs. These parked trucks are obstructing the adjacent bicycle lane, which is marked by white stripes. Bicyclists have to ride their bikes towards the left side of the bicycle lane, thus exposing themselves to vehicular traffic in the adjacent travel lane.

The space between bicycle lanes and CVLZs has multiple and conflicting demands. Clarity on this subject matter is important to preempt conflicts between truckers and cyclists, both of whom increasingly come into conflict on city roads.

Figure 1.2 Truck impeding a bike lane (Credit - Anna Alligood)

Figure 1.3 Trucks impeding a bike lane (Credit - Anna Alligood)

For this research project, The Pacific Northwest Transportation Consortium (PacTrans) partnered with the University of Washington (UW) and Oregon State University (OSU) on a research project to improve cyclist safety and design elements of a CVLZ in urban environments.

This project tested the impacts of different striping and signage on cyclist behavior around commercial vehicle (truck) loading zones and determined the implications for cyclist safety. In this study, we modeled a dense urban environment in OSU's Bicycling Simulator. The simulator allowed us to more accurately identify the causal mechanisms of crashes between trucks and bicycles, and the variables that contribute to them. Our end goal was to better understand the relationship between truck movements in and around load zones and bicyclist behavior, and ultimately, to improve road safety.

This report summarizes our research methods and findings, and includes information about the following:

- Literature Review – A summary of cyclist behavior and the outcomes of previous cycling simulation studies
- Experimental Design and Coding of the Simulation Test Environment – Development of a statistically sound (counterbalanced factorial experimental design) research approach based on interactions with the cyclist community, design of test environments, shared designs with stakeholders, and use of the OSU Bicycling Simulator to test and evaluate designs
- Sampling and Subject Recruiting Plan – Recruitment of 30-60 participants for the study
- Simulator Experiment – Tests using participants and the OSU Bicycling Simulator
- Analysis of Results – Recording and analysis of the data: instantaneous velocity, lateral position, and acceleration/deceleration.

2. Literature Review

2.1 Cyclist Fatalities

Growing concerns over the 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 non-motorized modes of transport (Abadi et al., 2018). This has in turn increased the popularity of bicycles. Indeed, as traffic congestion has grown in urban areas, many cities have encouraged bicycling as a functional alternative to cars. Bicycling has the advantage of being less infrastructure-intensive than public transportation, and has a significantly 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 amount of bicycle commutes between 2007 and 2017 (SDOT, 2007) and Portland, Oregon, adopted a Bicycle Plan that aims to achieve a 25 percent mode share by 2030 (PBOT, 2010).

However, as bicycling grows in popularity, conflicts between bicycles and other vehicles have become increasingly problematic. Figure 2.1 shows that despite the decrease in the total number of fatalities, the percentage of cyclist fatalities has increased considerably during recent years, as shown by data collected from the Fatality Analysis Reporting System (FARS 2016). More specifically, a growth in cyclist fatalities occurred in 2004. In just a decade, the percentage of cyclist fatalities among total fatalities increased from 1.47 percent in 2003 (42,884 fatalities – 629 cyclist fatalities) to 2.28 percent in 2013 (32,894 fatalities – 749 cyclists fatalities).

A study of bicycle accident data from the City of Seattle designed to evaluate the scale of bike-truck accidents used data from December 1, 2004, to April 8, 2014. During that period, 75 bicycle-truck accidents, including three fatalities and ten serious injuries, occurred. The fatality rate for bicycle-truck accidents was 4 percent, and the serious injury rate was 13 percent. In comparison, the rate of fatalities for all Seattle roadway bicycle accidents during the study period was 0.4 percent, and the serious injury rate was 7.6 percent, indicating that bike-truck accident are more severe. Bicycle-truck accidents made up 2 percent of all bicycle accidents. In addition, alcohol was indicated as a factor in one of the 75 accidents. Speeding was not indicated as a factor in any of the 75 accidents (Butrina et al., 2016).

A study by Conway et al (2013) investigated conflicts between commercial vehicles and bicycles in New York City. Several blocks were observed, and conflict rates between bicyclists and trucks were calculated for different neighborhoods, retail densities, and bicycle lane configurations. The lane configurations observed included a standard bicycle lane to the left of the parking curb space, bicycle lanes to the left of the curb space with a striped buffer zone between the bicycle lane and the vehicle travel lane, and bicycle lanes between curb-parked vehicles and the sidewalk. All these lane configurations are used in Seattle. In the NYC study, lanes between parking and the sidewalk had the lowest incidence of conflict between cyclists and trucks, while buffered lanes between parking and travel lanes had the highest. The authors speculated that the buffered bicycle lanes may be more attractive to truckers, who double park there because the buffer zone enables them to protrude less far into other travel lanes (Conway, et al 2013).

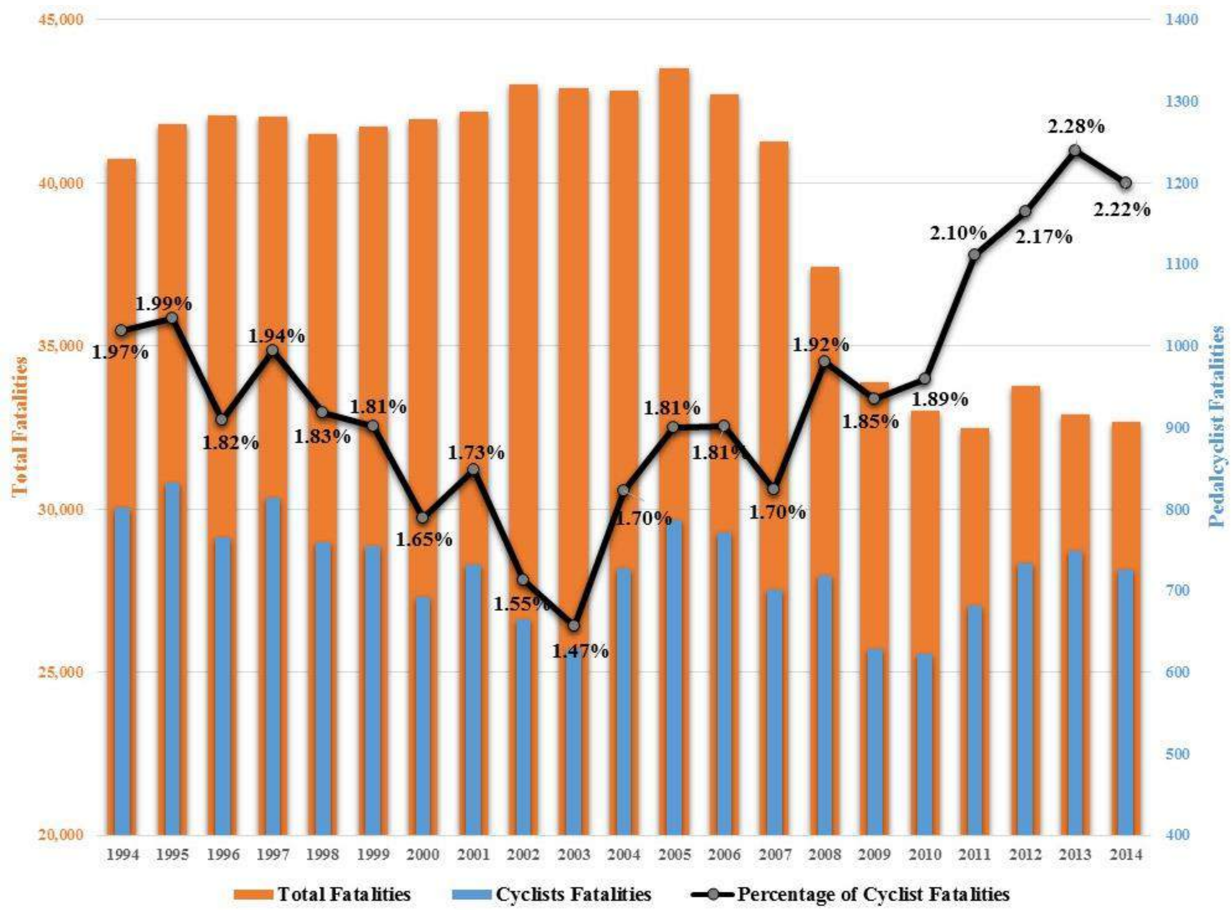


Figure 2.1 Traffic fatality trends (NHTSA, 2014, 2015, 2016a, 2016b)

Bicycle conflicts with freight vehicles are a notable problem because of the commonly severe consequences of collisions. Figure 2.2 shows that in recent years, large trucks have been the only vehicle classification that is overrepresented in cyclist fatalities. For example, in 2014, while large trucks made up only 3.67 percent of registered vehicles in the U.S., they were involved in 8.13 percent of cyclist fatalities.

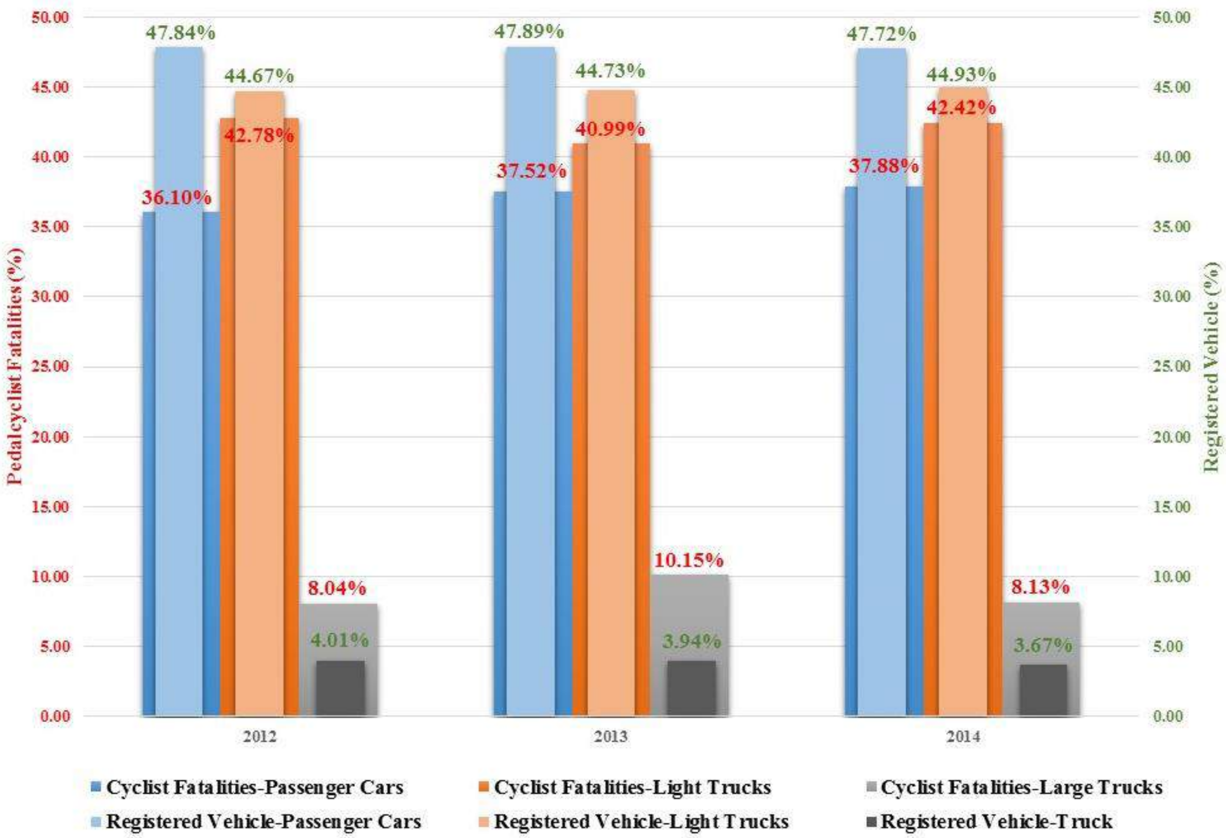


Figure 2.2 Cyclist fatalities by vehicle type (NHTSA, 2014, 2015, 2016a, 2016b)

Table 2.1 presents the initial point of contact in fatal cyclist crashes with large trucks. Large trucks most frequently collide with a bicycle from the front, which could indicate a right turning truck failing to yield the right-of-way to a through moving bicycle. This scenario can occur because of limited visibility and large blind spots to the left and right side of a large truck.

Table 2.1 Initial Point of Contact in Cyclist Fatalities (NHTSA, 2014, 2015, 2016a,)

Year	Front		Right Side		Left Side		Rear		Other/Unknown	
	No.	%	No.	%	No.	%	No.	%	No.	%
2012	32	54.2	13	22.0	2	3.4	3	5.1	9	15.3
2013	29	38.2	20	26.3	6	7.9	12	15.8	9	11.8
2014	30	50.8	17	28.8	3	5.1	2	3.4	7	11.9

2.2 Bicycle Simulators

Significant time has passed since the emergence of primitive flight simulators at the French Ecole de Combat in 1910 (Moore, 2008). Since then, a variety of automobile, truck, ship, motorcycle, and bicycle simulators have been developed and 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; Jeong et al., 2006). However, very few studies have employed bicycling simulation in the context of transportation safety.

2.2.1 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 (figure 2.3).

Cueing systems involve stimulation of all rider sensory and perceptual systems. In each of the cueing systems, 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 significant independent inputs from dynamic roadway elements (Fisher et al., 2011).

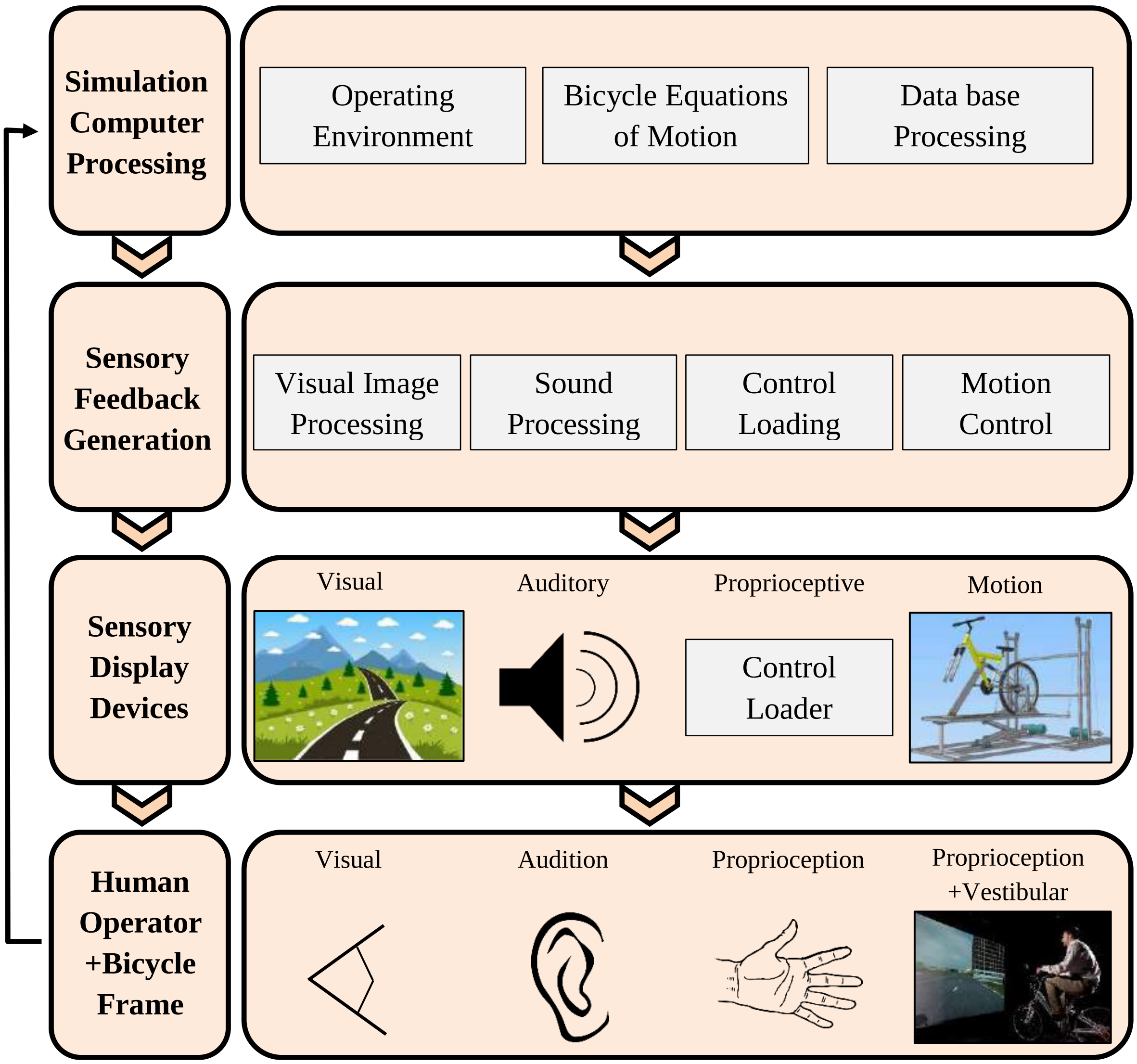


Figure 2.3 Components of a bicycle simulator (adopted from Fisher et al., 2011)

2.2.2 Examples of Bicycle Simulator Designs

The Virtual Environments Laboratory at the Max-Planck-Institute for Biological Cybernetics in Tubingen, Germany, was one of the earliest labs to feature a novel bicycle simulator in 1997. The simulator included a large curved projection screen in the form of a half-cylinder with a 23-ft (7-m) diameter and 10.3-ft (3.15-m) height (figure 2.4). For an observer seated in the center of the cylinder, this image covered a visual angle of 180 ° (horizontally) × 50 ° (vertically). Participants of studies conducted in this simulator could interact with the virtual environment by pedaling with force-feedback on the bicycle simulator or by hitting buttons. At each intersection, turns could be performed by pressing the left or right button on the bicycle (Steck et al., 2002).

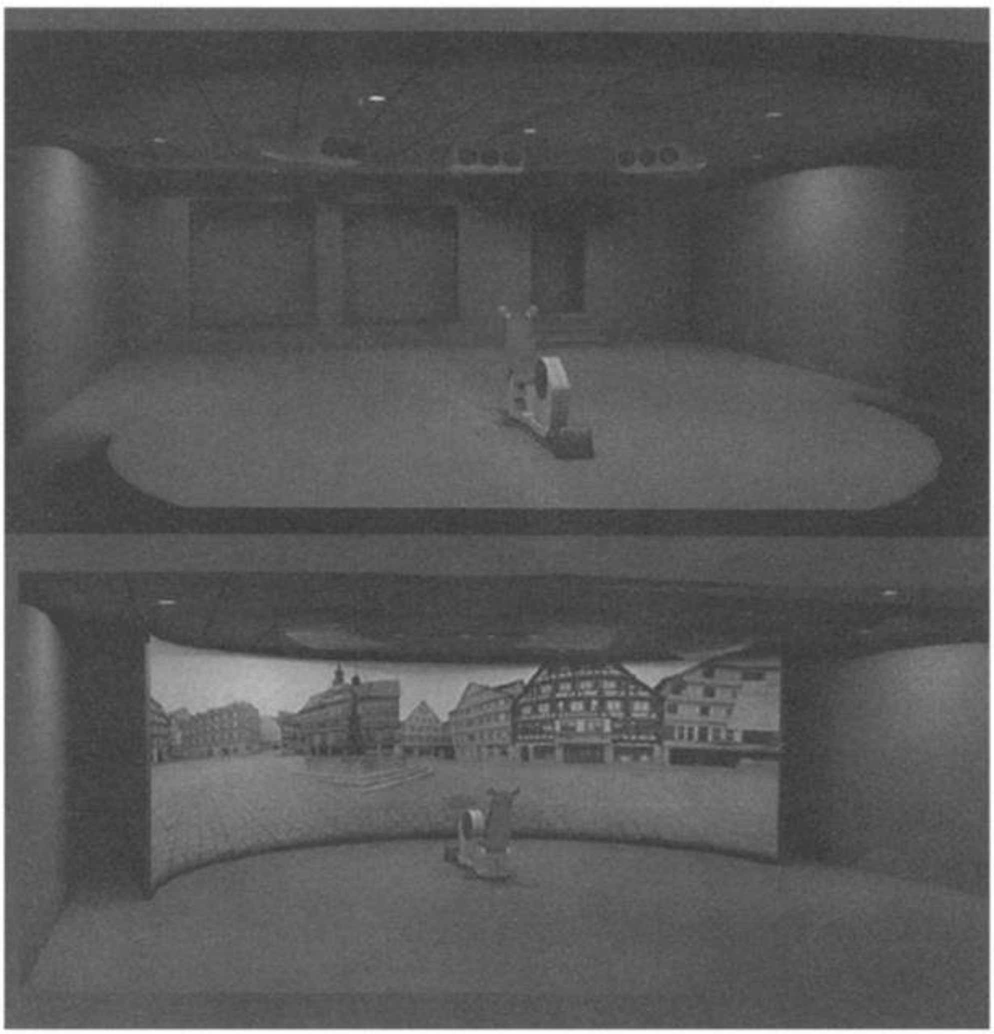


Figure 2.4 Early bicycle simulator at Max-Planck Institute (Van Veen et al., 1998)

After a series of improvements in 2005 and 2011, the lab features a cylindrical screen with a curved extension onto the floor, providing a projection surface of 230° (horizontally) × 125° (vertically—25° of visual angle upwards and 100° downwards from the normal observation position) (figure 2.5). The resulting surface is entirely covered by six EYEVIS LED DLP projectors with a resolution of 1920 × 1200 pixels each. Image generation is handled by a new render cluster consisting of six client image generation PCs and one master PC. Several types of input devices can be utilized in this virtual reality system. For example, participants in the experiment can interact with the virtual environment via actuated helicopter controls, steering wheels or bicycles (PanoLab, 2016).

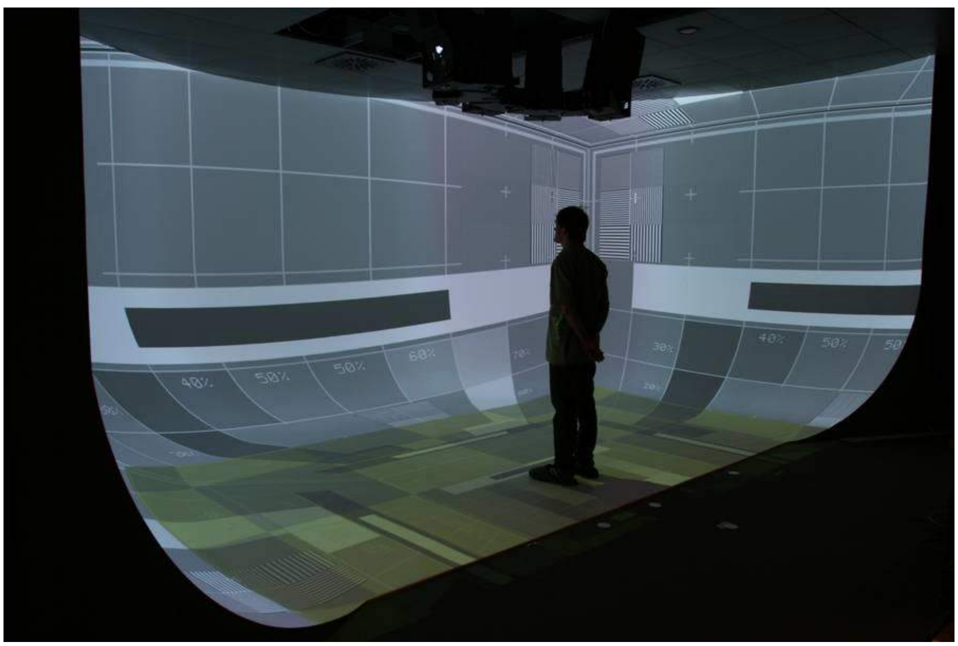


Figure 2.5 PanoLab at the Max-Planck Institute (PanoLab, 2016)

The bicycling simulator in the Hank Virtual Environment Lab at the University of Iowa, built in 1999, was one of the earliest bicycle simulators in the U.S. (Hank Lab, 2016). After major improvements in 2014, this simulator consists of three screens placed at right angles to each other (figure 2.6). The front screen measures 10 ft × 8 ft (3.05 m × 2.44 m). The two side screens are 14.22 ft × 8 ft (4.33 m × 2.44 m). Three DPI M-Vision 400 Cine 3D projectors are used to rear-project high-resolution, textured graphics in stereo onto the screens with a resolution of 1920 × 1080 pixels on each screen. An identical projector is used to front project high-resolution stereo images onto the floor. When configured as a bicycling simulator, an instrumented bike mounted on a stationary rig is used. The rear wheel rests on a flywheel connected to a torque motor, which controls the rate of rotation of the rear wheel and, hence, the load sensed by the rider. The bicycle dynamics software accounts for rider and bicycle mass and inertia, virtual terrain slope, ground friction, and wind resistance. The simulator includes a 12-camera Optitrack passive optical tracking system.

Figure 2.6 The Hank Lab at the University of Iowa (Hank Lab, 2016)

The FIVIS bicycle simulator at Bonn-Rhein-Sieg University of Applied Science in Sankt Augustin, Germany, features a dynamic bicycle simulator mounted on a motion platform with six degrees of freedom (FIVIS, 2016). The platform (including bicycle and cyclist) is placed within a set of three projection screens each 4.46 ft × 3.35 ft (1.36 m × 1.02 m), providing 180°

of immersive environment (figure 2.7). The computer-generated data are projected with three standard rear screen projection units. Matrox’ TripleHead2Go technology combines the three projectors to a single virtual screen with three viewports of 1024 × 768 pixels (Herpers et al., 2008). The bicycle is firmly attached to the platform and is equipped with a set of actuators and sensors to control pedaling resistance, steering torque, speed, front brake, and steering angle (Schulzyk et al., 2008).

Figure 2.7 FIVIS bicycle simulator at the Bonn-Rhein-Sieg University of Applied Science (Schulzyk et al., 2008)

The LEPSIS lab at the French institute of science and technology for transport, development, and networks features a bicycle simulator composed of a real bike on a stationary platform (figure 2.8). The visual display provides a visual angle of 225° (horizontally) × 55° (vertically) (LEPSIS, 2016) and image resolution of 1280 × 960 pixels (Caro & Bernardi, 2015). Two force-feedback systems provide haptic feedback: one in the handlebar and the other in the rear wheel. The inertia experienced by riders when they start or stop pedaling is produced by a flywheel. A fan, placed in front of the bicycle, simulates the air that would flow by the rider in a real-world situation (IFSTTAR, 2016a).

Figure 2.8 LEPSIS Lab bicycle simulator at the IFSTTAR (IFSTTAR, 2016b)

Lunghwa University of Science and Technology in Taoyun City, Taiwan, features a bicycle simulator composed of an urban bicycle placed on a stationary platform (figure 2.9). A real-time, fully textured, anti-aliased, three-dimensional graphical scene of a virtual world is projected at a resolution of 1024 × 768 pixels onto a 8.37-ft (2.55-m) back-projection acrylic screen in front of the cyclist. The total horizontal field of view is 85.5°, and the vertical field of view is 69.4°. The bicycle is equipped with sensorized brake levers (to measure brake status), rear wheel proximity switches (to measure speed) and front wheel variable resistors (to measure wheel rotation angles) (Liu et al., 2012).

Figure 2.9 Bicycle simulator at Lunghwa University of Science and Technology (Liu et al., 2012)

Oregon State University's bicycling simulator consists of an instrumented urban bicycle placed on top of an adjustable stationary platform (figure 2.10). A 10.5-ft × 8.3-ft (3.20-m × 2.54-m) screen provides the forward view with a visual angle of 109° (horizontally) × 89° (vertically) and image resolution of 1024 × 768 pixels. In addition, a small window on the top left corner of the screen acts as a rear view mirror (Horne et al., 2018).

Figure 2.10 Bicycle simulator at Oregon State University (OSU)

This research project used the Oregon State University (OSU) bicycling simulator. This 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. Moreover, to increase the demographic variety of subjects, three different bicycles (men's, women's, and a smaller children's size) are instrumented and can be traded off of the adjustable platform.

Looking at the examples of bicycle simulator designs around the world, table 2.2 summarizes the major characteristics of the labs that features these bicycle simulators.

Table 2.2 Bicycle simulator labs

Characteristics	**PanoLab**	**Hank**	**FIVIS**	**LEPSIS**	**Taiwan**	**OSU (used for this research)**
Location	Germany	USA	Germany	France	Taiwan	USA
Developer	Max Planck Institute for Biological Cybernetics	Department of Computer Science, The University of Iowa	Bonn-Rhein-Sieg University of Applied Science	French institute of science and technology for transport, development and networks	Lunghwa University of Science and Technology	Realtime Technologies, Inc.
Software	N/A	HCSM	FIVSim	N/A	N/A	SimCreator
Degree of Freedom	2	2	6	2	2	2
Visual Angle	230° (H) 125° (V)	270° (H) N/A (V)	180° (H) N/A (V)	225° (H) 55° (V)	85.5° (H) 69.4° (V)	109° (H) 89° (V)
Resolution	1920×1200	1920×1080	1024×768	1280×960	1024×768	1024×768

2.2.3 Examples of Bicycle Simulator Experiments

One of the first studies that utilized the Max-Planck-Institute bicycle simulator investigated the role of geographical slant in navigation and spatial memory tasks (Steck et al., 2002). Three identical environments varying only the slant conditions (flat, slanted NW and slanted NE) were used, with twelve participants in each group (total of 36 participants, 18 males, 18 females and aged 15-31). The experiment had four different phases: navigation, pointing judgment, elevation comparison, and map drawing. The authors determined that geographical slant plays a role either in the construction of a spatial memory or in its readouts or both and ultimately concluded that geographical slant improves pointing judgment, and geographical slant is incorporated into the human spatial representation of the environment.

In one of the earliest applications of a bicycle simulator in the U.S., 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 getting hit by a car. Participants faced cross-traffic from their left-hand side and waited for gaps they judged to be adequate for crossing. The cross-traffic traveled at a constant speed of either 25 mph or 35 mph, with varying temporal gaps between vehicles. Three issues were investigated: 1) Are there age differences in the size of traffic gaps that 10- and 12-year old children and adults accept? 2) do children and adults take into account the speed of the oncoming traffic when choosing a gap to cross? 3) How do 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 then used to quantify the following crossing behaviors of participants as: 1) stopping, 2) waiting time, 3) gap choice, 4) time left to spare, and 5) start-up time. The results of a repeated measures ANOVA revealed that there were no age differences in the size of gaps that children and adults accepted but children left less time to spare between themselves and the approaching vehicle.

Plumert et al. (2004) concluded that relative to adults, children's gap choices and road-crossing behavior were mismatched. Children and adults chose gaps that were virtually identical in size, 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 because of 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 children's and adult cyclists' gap choices and movement timing changed over a single experimental session in response to general and specific experience with crossing traffic-filled intersections in a virtual environment.

In the Plumert et al. (2011) study, a total of 72 participants in three age groups (10-year-olds, 12-year-olds, and adults) took part in a bicycle simulator experiment. Each age group consisted of 24 participants with an equal number of males and females. All participants bicycled across 12 intersections with continuous cross-traffic coming from their left-hand side. In the control condition, children and adults encountered randomly ordered gaps ranging from 1.5 to 5.0 sec 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 sec. Thus, the first four and last four intersections were the same for both groups, but the middle four intersections differed. In this study, general experience referred to the gap acceptance of the control group between the first and last set of intersections, and specific experience referred to the difference of gap acceptance between the first and last set 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 experience. Participants in both conditions were more likely to accept shorter gaps at later intersections than at the initial intersection. The tendency to accept smaller gaps at later intersections was also 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. Moreover, when confronted with high-density traffic, individuals who waited less and accepted shorter gaps were also more likely to take very short gaps at subsequent intersections even though bigger gaps were readily available. They also found 10-year-olds were more adaptive than 12-year-olds with respect to this road-crossing task, and as a consequence, they had more room for improvement.

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. In this study, scenarios were developed in which a motorcycle made a right turn ahead of a young cyclist. Two factors of speed difference and cut-in time gap were generated, each at three levels, making nine different experimental scenarios. Subsequently, distributions of the mean and standard deviation for steering angle and speed were analyzed in a series of mixed repeated-measures ANOVA with gender as a between-subjects factor and speed difference and cut-in time gap as within-subjects factors. In addition, a k-means cluster analysis was performed to investigate the response patterns characterized jointly by the speed measurements. This way, all 522 experimental conditions were assigned to five clusters as follows: 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 over the time of the event from the time the event motorcycle started to cut in to the time it 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, young 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 various sensory cues in cyclists' speed perception in a virtual environment. Twelve volunteers, between the ages of 21 and 46, participated in the experiment. Four experimental conditions were tested: a reference condition, a reduced visual speed condition, a reduced force feedback condition, and a reduced air flow condition. In the reference condition, the sensory cues were consistent with the cyclists' own speed, while in the three other conditions, the sensory cues were manipulated.

The results indicated that a change in the visual speed or in the force feedback affected the participants' speed, in the sense that the increase in speed produced by participants reflected a decrease in the perceived speed. Regarding air flow, although most of the participants indicated they were using it as a cue, it had no effect on the produced speed. However, on the basis of the small difference observed in the produced speed, they 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.

2.3 Bicycle-Truck Crashes

Few studies have investigated the issues associated with bicycle and truck crashes. One of the earliest studies (Riley and Bates, 1980) showed that heavy goods vehicles (HGVs) commonly cause cyclist deaths by side impact, and that the majority of cyclists die from multiple injuries associated with being run over by the wheels of the HGVs. Gilbert and McCarthy (1994) investigated 178 fatal crashes involving cyclists in greater London. On the basis of traffic data from the department of transport and police reports from January 1985 to December 1992, they found that HGVs were more frequently involved in cyclist fatalities than expected, both in relation to the proportions of traffic in London and compared with the national data on vehicle types involved in cyclist fatalities. They stated that from estimates of vehicle use in London, the risk of HGVs being involved in fatal crashes with cyclists in inner London could be estimated at five times that of buses, 14 times that of light goods vehicles (LGVs), and 30 times that of passenger cars. Later, Gilbert and McCarthy (1996) used a more comprehensive data set to investigate the same problem. They concluded that HGVs were involved in a higher proportion of fatal crashes involving female cyclists (66 percent) than males (28 percent).

Kim et al. (2007) developed a probabilistic model of cyclist injury severity in bicycle–motor vehicle crashes. This study used 2,934 bicycle crashes, based on police-reported crash data from the State of North Carolina for the years 1997–2002. The cyclist injury severity was classified as one of four categories: fatal injury, incapacitating injury, non-incapacitating injury, and possible or no injury. In this study, the overrepresentation of heavy trucks in bicycle fatal crashes was highlighted. Although heavy trucks accounted for only 1.8 percent of crashes in the data set, the authors found that if a heavy truck was involved, the percentage of fatal injury was 15.1 percent.

Statistical analysis of the results from a multinomial logit model indicated that heavy vehicles (HVs) are linked to an increase in the probabilities of both fatal and incapacitating injury in crashes and that when a bicycle collides with a HV, the cyclist is more likely to suffer a fatal injury. On the basis of the results of this study, if a HV is involved in a crash with a bicycle, the likelihood of fatal injury for the cyclist increases by 380.9 percent and the likelihood of incapacitating injury increases by 101.8 percent. Kim et al. (2007) related this increase in the probability of more severe injuries to the fact that HVs have greater momentum at a particular speed than passenger cars.

Moore et al., 2011 investigated the level of injury severity sustained by crash-involved cyclists at intersections and non-intersections, using data from 10,029 crashes between bicycles and motor vehicles from 2002 to 2008 in Ohio. Results of discrete outcome models indicated that cyclist collisions with large trucks dramatically increased the degree of injury severity. They found that in the case of bike-truck crashes, the likelihood of cyclist severe injury increases by 99.9 percent at intersection locations and 122.4 percent at non-intersection locations. Moore et al. (2011) related this finding to the shear difference in size, mass, and force of bikes and trucks.

In one of the rare studies specifically focused on bicycle-truck conflicts, Conway et al. (2013) investigated vehicle and surrounding area characteristics that influence the conflicts between commercial vehicles and bicycles in dense commercial centers in New York City. Conflicts were defined as events during which a cyclist was required to 1) deviate from the bicycle lane, 2) move farther into a vehicular travel lane or parking lane, or 3) stop (in or outside of a bicycle lane) to avoid a potential collision with a commercial vehicle. Collecting field data, 250 commercial vehicle arrivals and 35 conflict events were recorded in the field. Conway et al. investigated the influence of specific variables such as vehicle type, parking regulations and bicycle lane configuration on the likelihood of conflicts between bicycles and trucks. More specifically, three lane types were defined (figure 2.12): a standard Type A bicycle lane; a buffered Type B Llne; and a parking-buffered Type C lane.

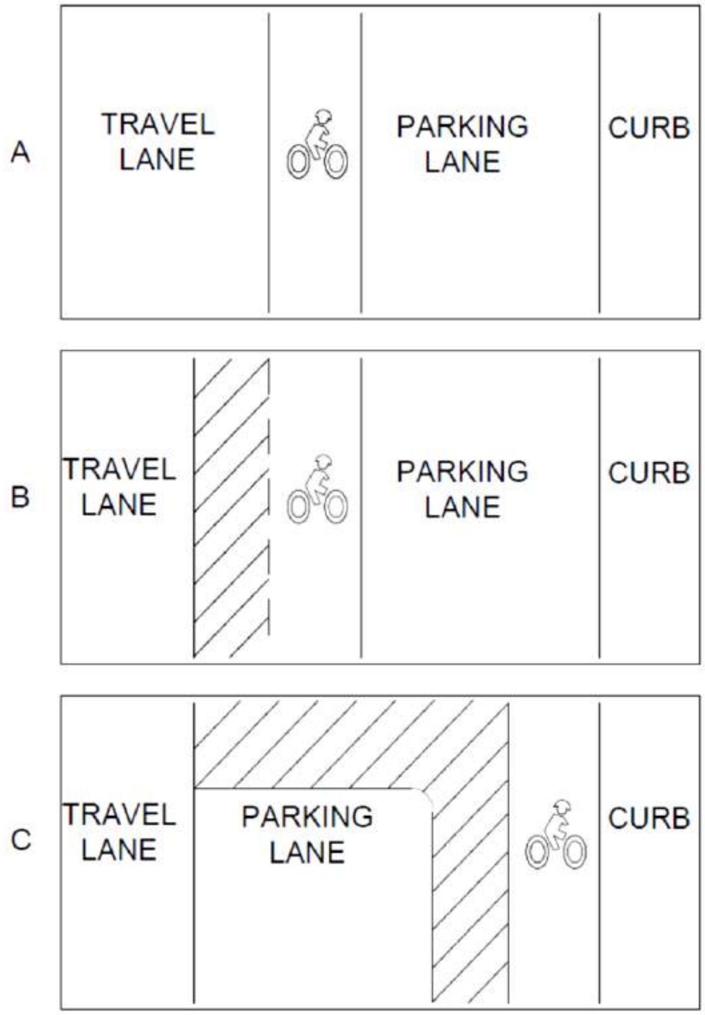


Figure 2.11 Bicycle lane configurations (Conway et al., 2013)

The authors observed that on average, conflict frequencies were nearly equal in Manhattan and Brooklyn, with about 14 percent of commercial vehicles conflicting with a bicycle. These conflicts increased when commercial vehicles were parked in a “No Parking” zone and that trucks were nearly three times as likely as commercial vans to conflict with a bicycle.

They confirmed that conflict frequencies varied considerably for different bicycle lane configurations. Type C bicycle lanes were by far the safest lane design to prevent conflicts between commercial vehicles and bicycles, as parked vehicles prevent commercial vehicles from parking, partially or fully, in the bicycle lane. In contrast, Type B bicycle lanes appeared to invite commercial vehicle parking (and the conflicts that result). Conway et al. (2013) related this high conflict rate to the fact that in a Type B lane design, a commercial vehicle can double park in a bicycle lane and the adjacent buffer and remain protected from oncoming traffic in a vehicle lane.

Research on the behavioral components of how cyclists behave around trucks is lacking, but has been examined in Petr Pokorny's doctoral thesis, "A Multi-Method Approach to Exploring Risk Factors in Truck-Bicycle Encounters," (January 2018). His thesis explored bike-truck safety in Norway's urban areas. The multi-method approach to understanding risk factors between both modes included analyzing bike-truck crash data and minor encounters, reviewing fatal accident reports, surveying cyclists, interviewing truck company employees, reviewing street video footage, examining conflicts and behavior between modes, and associating elements of cyclist risk with urban road infrastructure. The bike-truck crash and minor encounters data revealed that Norway has a high rate of fatal crashes (more than 30 percent) between trucks and cyclists. The street video footage revealed that "encounters between right-turning trucks and straight riding cyclists were evaluated as most risky…" (Pokorny, 2018). Pokorny also suggested that "segregated green phases or specific layouts for advanced cycle boxes at signalized intersections" could limit bike-truck encounters (Pokorny, 2018).

2.4 Traffic Control Devices in Loading Zones and Bicycle Lanes

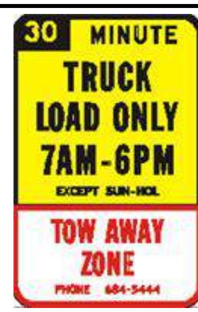
2.4.1 Traffic Signs and Curb Coloring in Loading Zones

There is no national standard for the signage and striping of loading zones. This section reviews common practices of signage and striping in various geographical locations, as well as those recommended in national regulations.

2.4.1.1 Seattle Department of Transportation (SDOT)

A load zone is a type of curb use that restricts a portion of the curb for loading and unloading activities. It is the second prioritization of curb use in Seattle (SDOT, 2016a). Load zones allow short-term use, such as 3 minutes or 30 minutes, for active loading and unloading, such as dropping off or picking up passengers or commercial loads (SDOT, 2016b). SDOT uses four distinct types of parking signs and terms to provide information about when, how long, and for what purposes a vehicle may use a load zone (table 2.3).

Table 2.3 Parking signs for loading zones in Seattle

Type of Load Zone	Generic	Passenger	Truck-only	Commercial Vehicle
Sign				
Time Limit	30 minutes	3 or 15 minutes	30 minutes	30 minutes
Metering	Unmetered	May be metered	Unmetered	Metered
Curb Color	Yellow	White	Yellow	Yellow
Purpose	To be used for several types of loading and unloading activities, including dropping off or picking up passengers, loading or unloading items from private vehicles (such as personal or company cars or trucks), and loading or unloading from items from commercial delivery vehicles.	To provide a place to load and unload passengers for adjacent dwellings and businesses. These are intended for quick passenger drop-offs and pick-ups, and should not be used for loading or unloading items from a vehicle.	To provide a place to load or unload products, merchandise, or other objects. Only vehicles licensed as trucks may use this type of load zone.	Commercial Vehicle Load Zones (CVLZ) are for commercial service delivery vehicles to conduct loading and unloading activities (such as trucks that deliver or pick up beverages, food supplies, large merchandise, etc.). Regular Truck-Only Load Zones do not adequately meet the needs of these vehicles.

2.4.1.2 San Francisco Municipal Transportation Agency (SFMTA)

Five types of color curbs are defined by the SFMTA to distinguish the utilization of public right-of-way: 1) red curbs: no parking, 2) white curbs: passenger loading/unloading, 3) green curbs/meters: short-term parking, 4) yellow curbs: commercial loading/unloading, and 5) blue curbs: parking for people with disabilities (SFMTA, 2016). Yellow zones are for active freight loading and unloading only by commercial vehicles. Drivers are asked to check nearby signs or stencils on the curb for effective hours. Six-wheel truck loading zones are indicated by signs only. When signed for six wheels or more, such trucks can use the zone. Six wheel loading zones can typically be distinguished by their red-capped meters in metered areas. Yellow zones are typically used for large businesses or properties that receive or deliver a lot of shipments. (SFMTA, 2016).

2.4.1.3 Manual on Uniform Traffic Control Devices (MUTCD)

Two signs are defined in the MUTCD to distinguish loading zones (figure 2.13).

Figure 2.12 Loading zone signs in the MUTCD (FHWA, 2009)

2.4.2 Traffic Signs and Pavement Markings for Bicycle Lanes

Bike lanes designate an exclusive space for cyclists through the use of pavement markings and signage (NACTO, 2011). The MUTCD (FHWA, 2009) defines three types of signs for bicycle facilities: 1) regulatory signs (Appendix A - figure A.1), 2) warning signs (Appendix A - figure A.2) and 3) guide signs (Appendix A - figure A.3). None of these signs directly address bicycle-truck interactions in loading zones.

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 2.14 illustrates general word, symbol, and pavement markings for bicycle lanes as defined by the MUTCD.

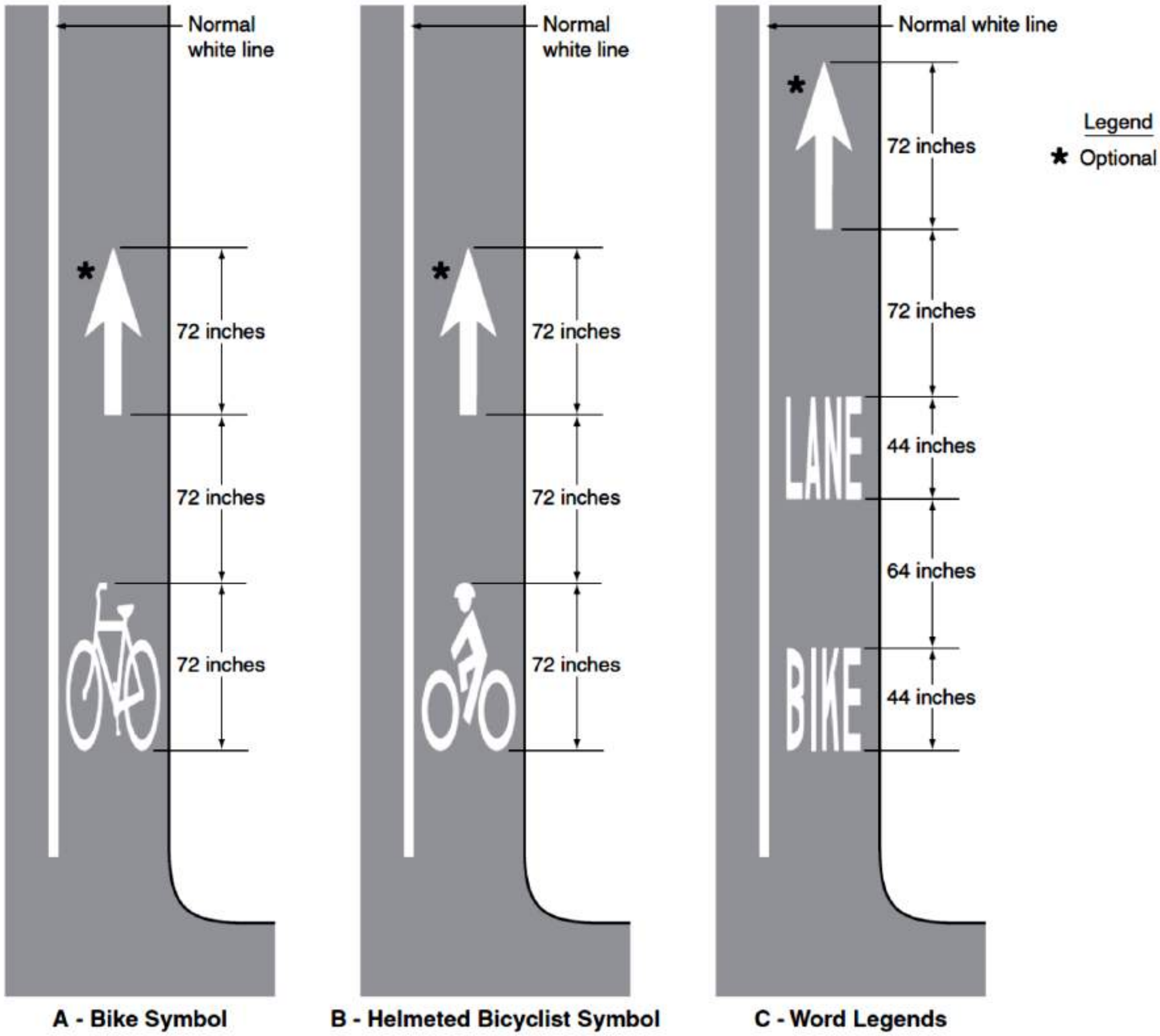


Figure 2.13 Word, symbol, and arrow pavement markings for bicycle lanes in the MUTCD (FHWA, 2009)

Colored pavement within a bicycle lane increases the 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 non-standard or enhanced facilities such as cycle tracks (NACTO, 2011). For example, regarding intersection crossings, the Urban Bikeway Design Guide

(NACTO, 2011) identifies four different crossing features, optional to use, including a combination of several of the features shown in figure 2.15.

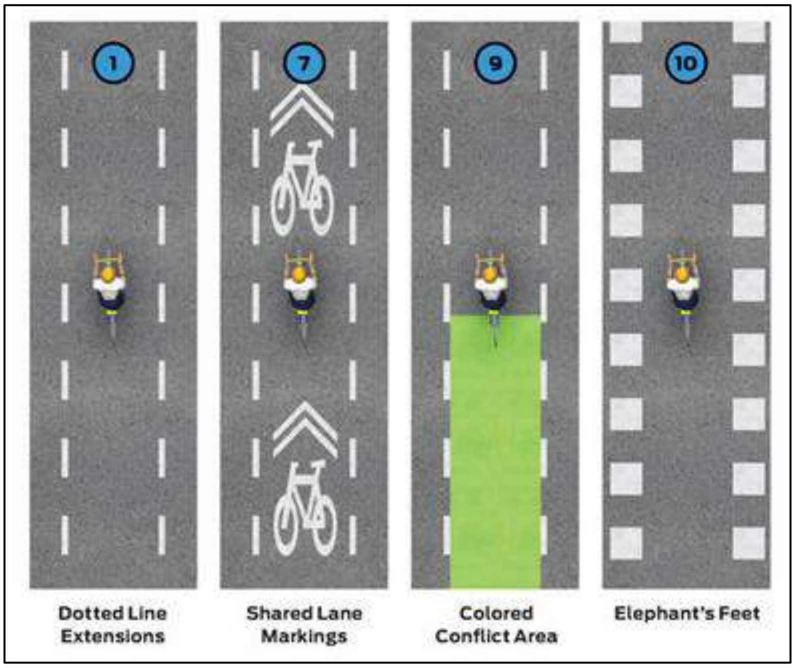


Figure 2.14 Pavement markings for intersection crossings (adapted from NACTO, 2011)

2.4.3 Bicycle Lanes through Loading Zones

The Separated Bike Lane Planning and Design Guide (FHWA, 2015) addresses the interaction of bicycles and trucks in loading zones by identifying two separate plans. The first alternative considers available on-street parking in the buffer space and then manages bike lanes through loading zones by restricting parking and conflicting pedestrian crossings (figure 2.16). Alternative 2 addresses situations in which there is no space that can be made available from on-street parking. In this plan, separated bike lanes are bent, and additional space is acquired either from the sidewalk (figure 2.17) through roadway widening, through reduction in vehicle travel lanes, or by creating a vehicle mixing zone with a separated bike lane.

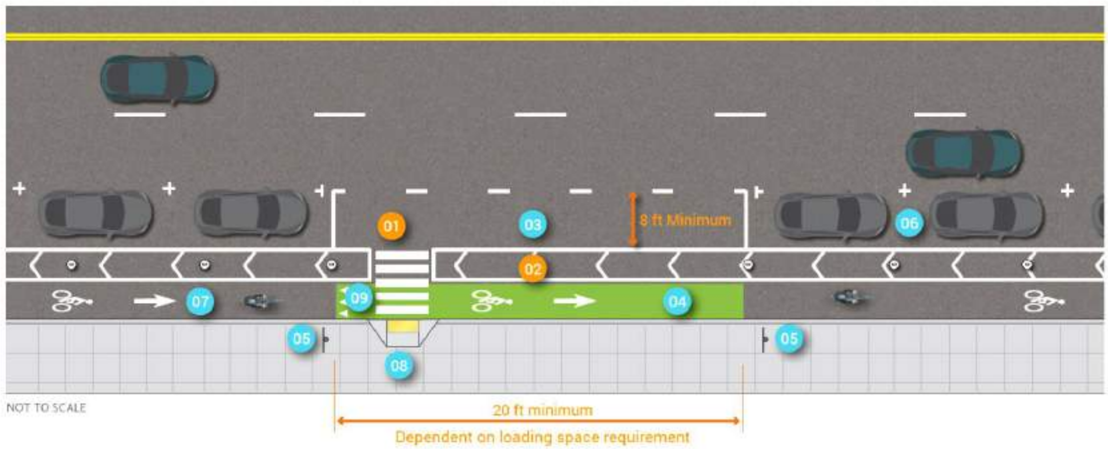


Figure 2.15 Separated bike lanes through loading zones – alternative 1 (FHWA, 2015)

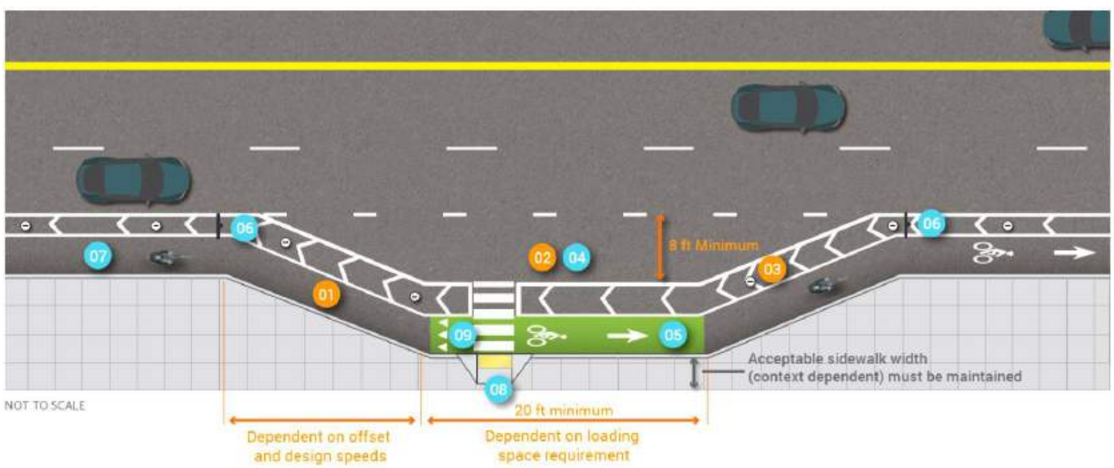


Figure 2.16 Separated bike lanes through loading zones – alternative 2 (FHWA, 2015)

2.5 Literature Review Summary

This literature review can be summarized into the following key points:

- As traffic congestion grows in urban areas, many cities are encouraging bicycling as a functional alternative to cars. However, as bicycling grows in popularity, conflicts between bicycles and other vehicles have become increasingly problematic. In just a decade, the percentage of cyclist fatalities among total fatalities in the United States increased from 1.47 percent in 2003 to 2.28 percent in 2013.

- In recent years, large trucks have been the only vehicle classification that is overrepresented in cyclist fatalities. Large trucks most frequently collide with a bicycle from the front.
- Different forms of bicycle simulators have been utilized in medical science, sport science, video games, and mechanical engineering. However, 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 gap acceptance and the road crossing behavior of children while bicycling and the response of cyclists to right-turning motorcycles.
- Six labs have been identified that feature novel bicycle simulators worldwide: 1) PanoLab at the Max Planck Institute for Biological Cybernetics in Germany, 2) Hank at the University of Iowa in the USA, 3) FIVIS at the Bonn-Rhein-Sieg University of Applied Science in Germany, 4) LEPSIS at the French institute of science and technology for transport, development and networks, 5) the bicycle simulator at the Lunghwa University of Science and Technology in Taiwan and 6) the bicycle simulator at Oregon State University in the USA, which was used in this research.
- Few studies have investigated the issues associated with bicycle and truck conflicts. In comparison to other types of crashes, it has been found that in the case of bicycle-truck crashes, the likelihood of a cyclist fatality and severe injury increases significantly. It has also been found that variables such as parking regulation and bicycle lane configuration affect bicycle-truck conflicts.

- There is no national standard for the signage and striping of loading zones. However, local agencies (such as SDOT and SFMTA) and federal guidance (such as the MUTCD) have recommended customized traffic signs and colored curbs.
- Three types of signs (regulatory, warning, and guidance) and general pavement markings are recommended for bicycle facilities by the MUTCD. Colored pavement markings are also suggested for bicycle intersection crossing by the Urban Bikeway Design Guide (NACTO, 2011).

3. Methods

This chapter describes the hardware and software associated with the Oregon State University (OSU) bicycle simulator, as well as the types of data collected for the bicycling simulator experiment. Additionally, it details the experimental protocol including the process for recruiting subjects, the sequence of activities participants were directed to perform during the experiment, and the pilot study of the experimental protocols.

3.1 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 that was used for this experiment, the OSU bicycling simulator, is described in detail in the following sections.

3.1.1 Truck Classes

The Federal Highway Administration (FHWA, 2014) defines 13 vehicle classes (figure 2.11). For the purpose of this study, trucks in class 5 of the FHWA vehicle classification were considered because this class includes city delivery trucks (Municibid, 2018). Trucks in class 5 complemented our intent to simulate an urban environment. As defined by FHWA (2014), this class of two-axle, six-tire, single-unit trucks includes all vehicles on a single frame, such as trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels.

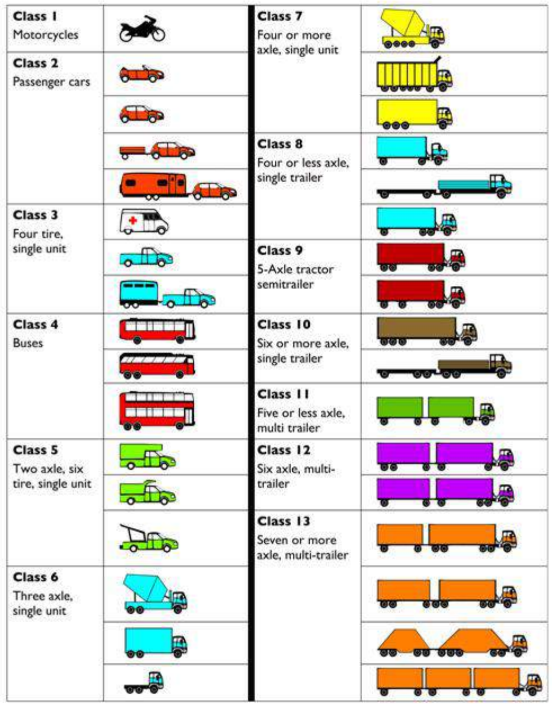


Figure 3.1 FHWA vehicle classification (FHWA, 2014)

3.1.2 Bicycling Simulator

As mentioned in Chapter 2, the OSU bicycling simulator consists of an instrumented urban bicycle placed on top of an adjustable stationary platform. A 10.5-ft × 8.3-ft (3.20-m × 2.54-m) screen provides the forward view with a visual angle of 109° (horizontally) × 89° (vertically) and image resolution of 1024 × 768 pixels. In addition, a small window on the top left corner of the screen acts as a rear-view mirror. Researchers build the environment and track subject bicyclists from within the operator workstation shown in figure 3.1, which is out of view from participants in the bicycle simulator experiment.

Figure 3.2 Operator workstation for the bicycling simulator.
Left: Real-time monitoring of the simulated environment. *Right*: A researcher designing an experiment in SimCreator

The update rate for the projected graphics is 60 Hz. Ambient sounds around the bicycle 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 3.3 shows views of the simulated environment created for this experiment from participant's view (left) and outside view (right).

Figure 3.3 Simulated environment in the OSU driving simulator.
Left: Participant's perspective. *Right:* A researcher checking a bicycle brake.

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

3.1.2.1 Simulator Data

The following parameters for both the subject bicycle 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 bicycle – To identify changes in speed approaching a loading zone or an intersection
- Instantaneous position of subject bicycle – To estimate the headways and distance upstream from the loading zone or the stop line
- Instantaneous acceleration/deceleration – To identify any acceleration or deceleration approaching the loading zone or intersection
- Instantaneous speed of dynamic vehicle – To record the speed approaching a loading zone or an intersection
- Instantaneous position of dynamic object– To locate the distance upstream from the loading zone or the stop line and to calculate the headway of the subject bicycle.

SimObserver data - The bicycling simulator was equipped with three cameras positioned at various viewing angles to observe the actions of participants when approaching a loading zone. Figure 3.4 shows the various camera views and screen captures that were recorded by SimObserver (Version 2.02.4).

Figure 3.4 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.

3.1.2.2 Simulator Sickness

Simulator sickness is a phenomenon in which 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 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 and physical motion cues, as perceived by the vestibular system (Owens and Tyrrell 1999). There is no literature in the area of bicycling simulation that would suggest motion sickness issues in bicycle simulation experiments. However, precautions were taken to ensure comfort for all of the participants.

3.2 Experimental Design

The bicycling simulator experiment examined bicycle and truck interactions. This was achieved by analyzing bicyclist behavior at and around commercial loading zones. The bicyclists' performance and crash avoidance were used to evaluate different pavement marking and signage.

3.2.1 Factorial Design

Three independent variables were included in the experiment: pavement marking, signage, and truck maneuver (table 3.1).

Table 3.1 Experimental factors and levels

Variable Name	Level	Levels Description
Pavement Marking	0	White Lane Marking
	1	Solid Green
	2	Dashed Green
Signage	0	None
	1	Warning Sign
Truck Maneuver	0	None
	1	Parked
	2	Exiting

For pavement marking levels, recommendations from the National Association of City Transportation Officials Urban Bikeway Design Guide (2011) were considered. Three levels of bike lane pavement markings were used (figure 3.5): 1) white lane markings with no supplemental pavement color (called "white lane markings" hereafter), 2) white lane markings with solid green color applied to the conflict area (called "solid green" hereafter), and 3) white lane markings with dashed green color applied to the conflict area (called "dashed green" hereafter).

Two levels of traffic signs were considered: 1) no sign and 2) a sign warning bicyclists of a potential truck conflict on the road. No specific sign is endorsed by MUTCD to address bicycle and truck conflicts. As a result, W11-10 (figure 3.6), a generic warning sign, was employed in this study. According to the MUTCD, a vehicular traffic warning sign (e.g., W11-10) may be used to alert road users to locations where unexpected entries into the roadway by trucks, bicyclists, farm vehicles, emergency vehicles, golf carts, horse-drawn vehicles, or other vehicles might occur" (FHWA, 2009).

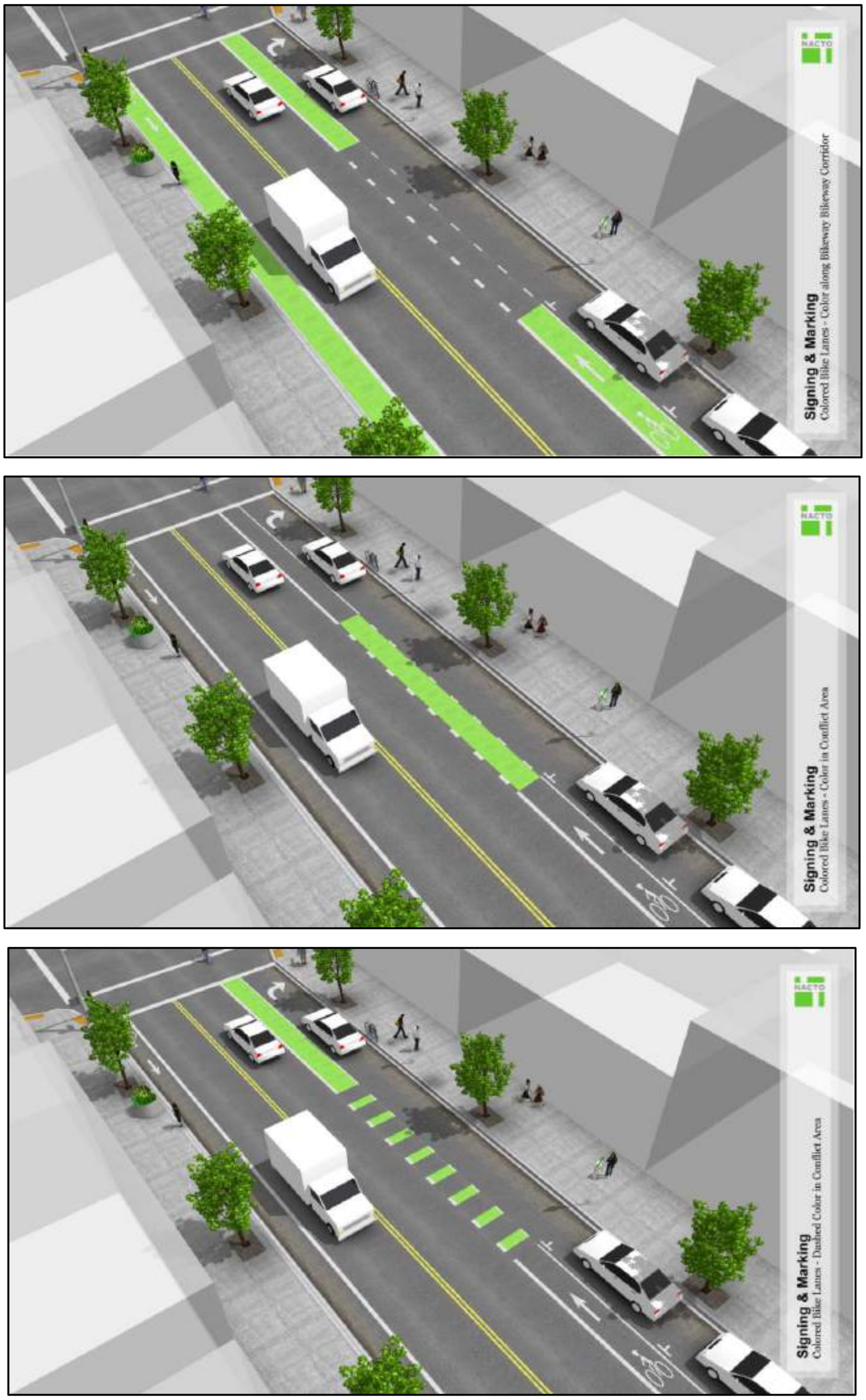


Figure 3.5 Three levels of pavement marking adopted from NACTO, 2011.
Top: White lane markings. *Center:* Solid green. *Bottom:* Dashed green.

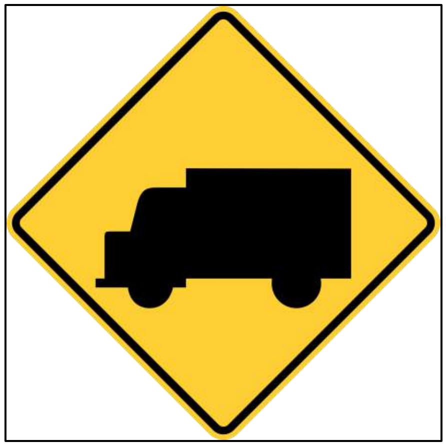


Figure 3.6 Warning sign W11-10 adopted from the MUTCD (FHWA, 2009).

Three levels of truck maneuver were considered: 1) no truck, 2) truck parked in a loading zone, and 3) truck exiting the loading zone 2.5 seconds before the bicyclist reached it. This cut-in time gap of 2.5 seconds was based on the accepted reaction times for motorists and bicyclists. Figure 3.7 shows scenarios with and without the truck presence.

Figure 3.7 Example scenarios in the simulated environment. *Left:* No truck. *Right:* Truck parked

These independent variables (factors) and levels resulted in a study with a 3×3×2 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 an on-street loading zone was created in one direction to account for bicycle-truck interactions.

3.2.2 Research Questions

The specific research questions associated with the assessment of the bicyclist performance and crash avoidance are presented in this sub-section.

3.2.2.1 Bicyclist Performance

The bicyclists' performance was measured in terms of velocity (m/s), lateral position (m), and acceleration (m/s^2). The potential influence of the experimental factors (table 3.1) on each of the response variables formed the basis of the research questions regarding the bicyclists' performance.

- *Research Question 1 (RQ1)*: Do engineering treatments and truck maneuvers have any effect on bicyclists' velocity in the bicycling environment?
- *Research Question 2 (RQ2)*: Do engineering treatments and truck maneuvers have any effect on bicyclists' lateral position in the bicycling environment?
- *Research Question 3 (RQ3)*: Do engineering treatments and truck maneuvers have any effect on bicyclists' acceleration in the bicycling environment?

3.2.3 Presentation of Bicycling Scenarios

Eighteen scenarios (table 3.2) were presented to participants across six grids. To measure the influence of treatment alternatives, participants were exposed to a variety of different treatment configurations.

Table 3.2 Cut-in scenarios

Experiment #	Cut-in #	Pavement Marking	Signage	Truck Maneuver
Grid 1				
6	1	White Lane Marking	Warning	Exiting
2	2		None	Parked
5	3		Warning	Parked
Grid 2				
4	1	White Lane Marking	Warning	None
1	2		None	None
3	3		None	Exiting
Grid 3				
8	1	Solid Green	None	Parked
12	2		Warning	Exiting
10	3		Warning	None
Grid 4				
7	1	Solid Green	None	None
9	2		None	Exiting
11	3		Warning	Parked
Grid 5				
17	1	Dashed Green	Warning	Parked
15	2		None	Exiting
13	3		None	None
Grid 6				
16	1	Dashed Green	Warning	None
14	2		None	Parked
18	3		Warning	Exiting

Figure 3.7 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.

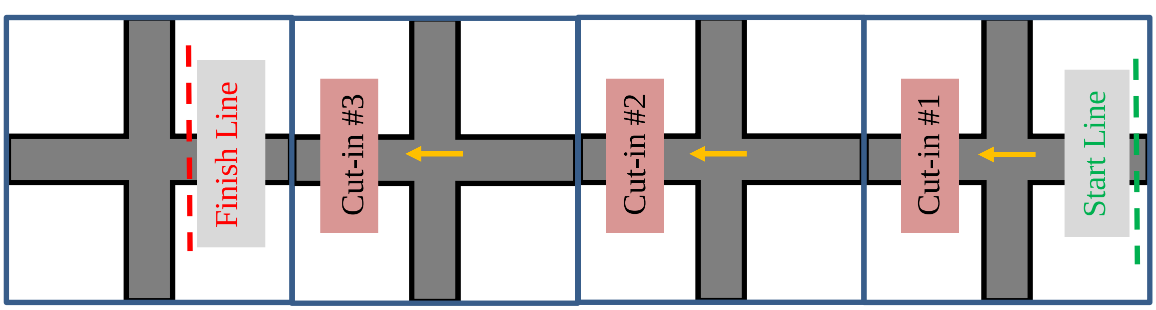


Figure 3.8 Example grid layout

3.2.4 Counterbalancing

To control for practice or carryover effects, the order of intersection grids was counterbalanced. In this randomized partial counterbalancing procedure, six different grid sequences were chosen. The grid sequences were as follows: 3-6-1-4-2-5, 5-1-6-2-4-3, 2-4-6-5-1-3, 4-5-1-2-3-6, 3-5-4-2-6-1, and 6-1-3-4-5-2.

3.3 Bicycling Simulator Experimental Protocol

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

3.3.1 Recruitment

Participants in this study were selected on the basis of the typical demographic of the bicyclist population available through researcher contacts at bicycle clubs and non-motorized user and demographic surveys completed by regional and national transportation departments. All participants were required to have the experience of riding a bicycle and to be physically and mentally capable of appropriately controlling a bicycle. All participants had to be competent to provide informed consent, and bicycling simulator subjects could not have vision problems that would prevent them from participation 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 and 50 females. Researchers would 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 would be allowed to participate. 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 range of 18 to 75. 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.

3.3.2 Informed Consent and Compensation

Upon the test participant's arrival to the laboratory, the informed consent document approved by OSU's IRB 7517 in Task 2 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 the experimental trial after signing the informed consent document.

3.3.3 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, as well as their prior experience with driving/bicycling 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 whether they used corrective glasses or contact lenses while driving/bicycling. This ensured during the test ride that the participants were able to clearly see the bicycling environment and to read the visual instruction displayed on the screen to stop the bicycling.

- Simulator sickness – Participants with previous driving/bicycling simulation experience were asked about any simulator sickness they had experienced. If they had previously experience simulator sickness, they were encouraged not to participate.
- Motion sickness – Participants weer 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.

3.3.4 Calibration Ride

A test ride followed the completion of the prescreening survey. At this stage, bicyclists were required to perform a 3- to 5-minute calibration ride to acclimate to the operational characteristics of the bicycling simulator, and to confirm whether they were prone to simulator sickness. Participants were instructed to ride and follow all traffic laws that they normally would. The test ride was conducted on a generic city environment track with turning maneuvers similar to those of this experiment so that participants could become accustomed to both the bicycle's mechanics and the virtual reality of the simulator (figure 3.9). In the case that a participant reported simulator sickness during or after the calibration ride, s/he was excluded from the experimental rides.

Figure 3.9 Calibration ride in simulation

3.3.5 Experimental Ride

Participants were given brief instructions about the test environment and the tasks they would be required to perform. The experiment was divided into six grids. The virtual bicycling course itself was designed to take the participant 20 to 30 minutes to complete. The entire experiment, including the consent process and post-ride questionnaire, lasted approximately 50 minutes.

3.3.6 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 six experimental rides. Files, including collected video data and all output of bicycle characteristics (e.g., lateral position and velocity), were opened in the *Data Distillery* (Version 1.34) software suite, which provided quantitative outputs (numerical and graphical) in combination with the recorded video. Figure 3.10 shows the *SimObserver* video output in conjunction with numerical data (right side) and graphical representations of data in columns (bottom) opened by *Data Distillery*.

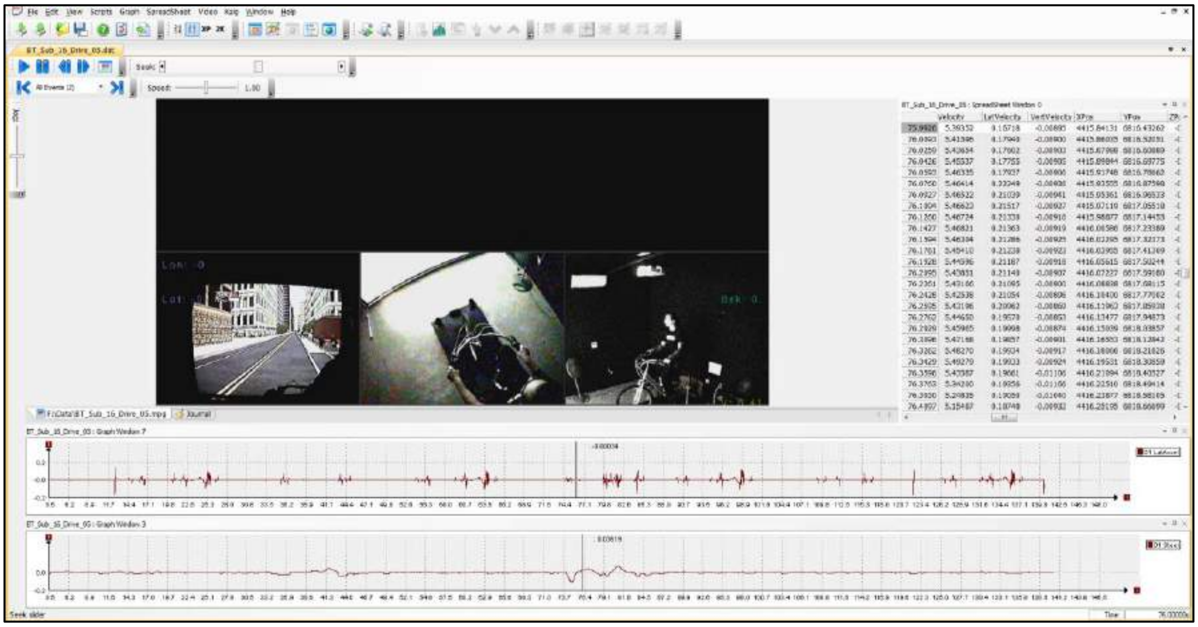


Figure 3.10 Screenshot of *Data Distillery* software interface

4. Results

This chapter presents the results of the simulator experiment. Section 4.1 describes the participant demographics. Section 4.2 investigates bicyclist's 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.

4.1 Participants

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

4.1.1 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). Table 4.1 shows participants' bicycling habits. Participants most frequently bicycled on a daily basis (52.1 percent), to commute to work/school (72.9 percent), and bicycled for 10-20 minutes on an average trip (50.0 percent). Additionally, over 83 percent of participants had experience with riding a bicycle in a busy downtown.

Table 4.1 Participants' bicycling habits

Bicycling Habit	Possible Responses	Number 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	Less than 10 minutes	15	31.3%
	10 – 20 minutes	24	50.0%
	20 – 30 minutes	5	10.4%
	More than 30 minutes	4	8.3%
Downtown Experience	Yes	40	83.3%
	No	8	16.7%

4.1.2 *Demographics*

Every effort was made to recruit a representative sample of Oregon bicyclists. Table 4.2 summarizes the self-reported demographic data of the final sample population.

Table 4.2 Participant demographics

Demographics	Categories	Number 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	Less than $25,000	21	43.8%
	$25,000 to less than $50,000	5	10.4%
	$50,000 to less than $75,000	7	14.6%
	$75,000 to less than $100,000	2	4.2%
	$100,000 to less than $200,000	6	12.5%
	$200,000 or more	3	6.3%
	Prefer not to answer	4	8.3%

4.1.3 *Post-Ride Survey Results*

After participants completed the bicycling simulator portion of the experiment, they were asked to complete a short survey regarding the bicycle simulator functionality and the effectiveness of the engineering treatments they encountered during their ride in the simulator. Results from two of the survey items are reported below. In order to verify the authenticity of the simulated bicycling task, participants were asked to subjectively evaluate the performance of the bicycle simulator. The ratings ranged from 0 to 10, where 0 was defined as completely different from real world experience, and 10 was defined as completely similar to real world experience. The average scores for each of the categories are shown in Table 4.3.

Table 4.3 Average scores of bicycling simulator authenticity

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

Evaluating whether there is a difference in the performance of bicyclists on the basis of the types of pavement marking used at the conflict point was another goal of the research. To better investigate this question, bicyclists' perceptions of different levels of pavement marking were evaluated in the post-ride survey. Participants were asked to indicate whether the three levels of pavement markings (figure 4.1) conveyed different information to them.

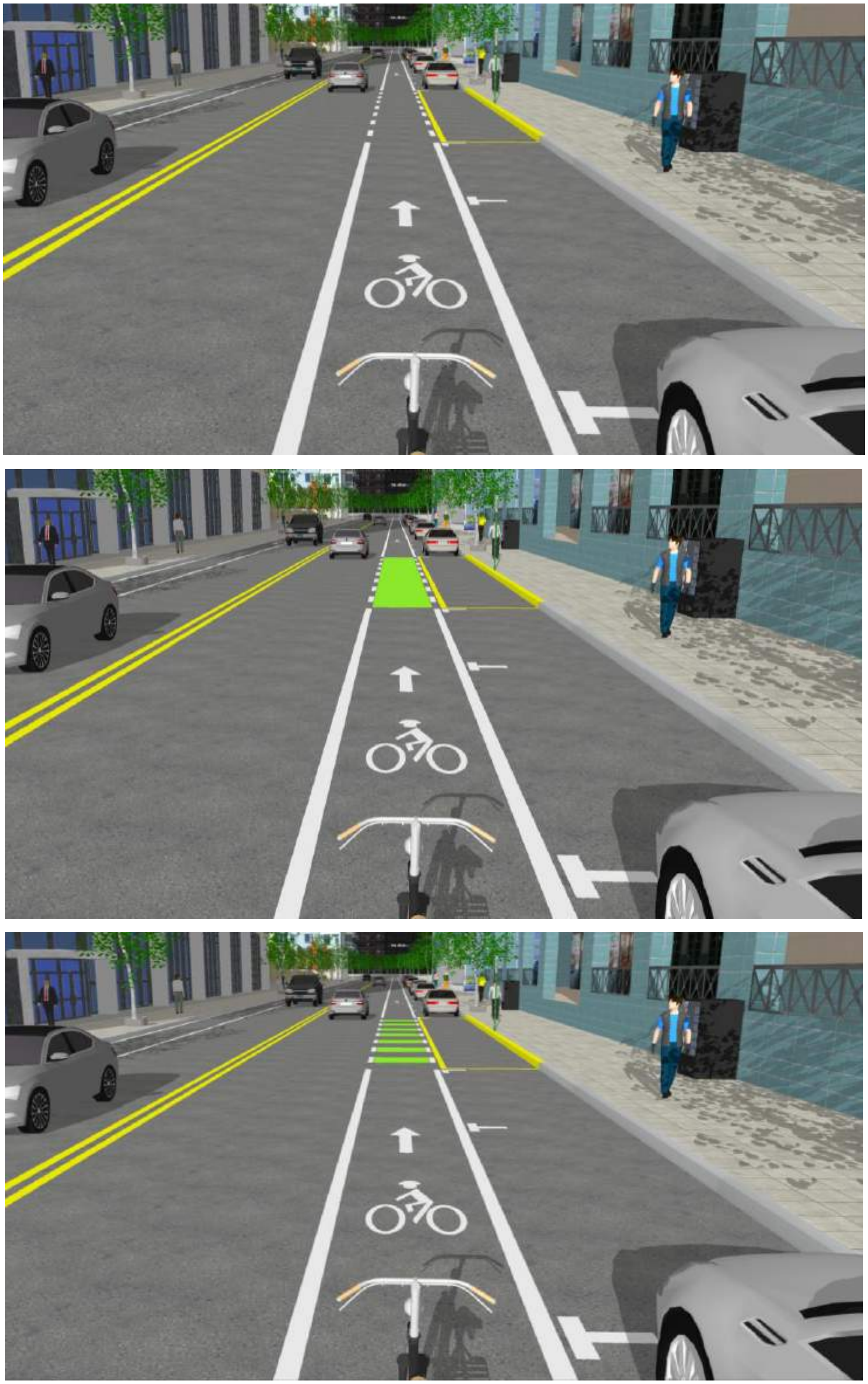


Figure 4.1 Three levels of pavement marking.
Top: White lane markings. *Center:* Solid green. *Bottom:* Dashed green.

Twenty-two out of 48 participants indicated that they did not perceive any difference among the three levels of pavement marking. From the 26 remaining, eight participants related the pavement markings to right-of-way negotiation between bicycles and vehicular traffic:

> "*I have the notion that the solid green box truly gives me the right of way, the dashed white & green I anticipate that I would need to yield.*" (60-year-old female participant).

> "*The green markings convey that the bicycle lane has the right of way in addition to highlighting the bicycle lane, whereas the first picture (with no green) would seem more dangerous from a bicyclist's point of view. I cannot discern a difference in meaning from the striped green to the solid green.*" (20-year-old male participant).

> "*Technically, the same legal interpretation. The impression they give, however, is different. For me personally, the first* [white lane marking] *implies no right of way, the second* [dashed green] *says bikes get precedence, but proceed with caution, and the third* [solid green] *implies that the bike has right of way.*" (40-year-old male participant).

Eight participants related pavement markings to increased road user awareness:

> "*The green bike lanes make it seem as if the bike lane was more meant for the bikers. It makes me feel that vehicles will look over their shoulder or in their mirrors before entering into the bike lane.*" (21-year-old male participant).

> "*I don't know of any standard, but the green striping usually indicates an area where motorists should be especially aware of bicycles.*" (71-year-old male participant).

> "*The green markers remind the bikers to be more aware of your surroundings because those are frequent load/unload areas.*" (19-year-old female participant).

Two of the participants expressed their bicycling comfort in relation to the pavement markings:

> "*The green area make me feel more comfortable. However, I prefer to pay attention to the loading/unloading trucks than the markings more.*" (38-year-old male participant).

> "*I identify green with more bike-friendly.*" (20-year-old male participant).

One other participant commented on the performance of different levels of pavement marking:

"*The solid color seems smoother, more likely to skid.*" (57-year-old female participant).

One participant related pavement markings to the design of loading zones:

"*The first photo without green does not look like a loading zone. The green ones do.*" (25-year-old female participant).

Finally, six participants indicated that they felt a difference in the message conveyed, but they were not sure about the message itself:

"*I don't have enough city bicycling experience to know, but I imagine these convey slightly different things.*" (18-year-old male participant).

4.2 Bicyclist Performance

The bicycling simulator collected a large set of data related to participants' bicycling experience including velocity, lane position, and acceleration throughout the entire simulation. To observe participants' behavior in proximity to adjacent loading zones, data were segmented so that the 12 meters before the loading zone and the 20-meter loading zone were observed. Twelve meters before the encounter was chosen to encompass the general area where the loading zone, possible truck, and possible warning sign were clearly visible to the bicyclist.

Because each participant was exposed to all possible combinations of independent variables, repeated-measures analysis of variance (ANOVA) tests were performed with pavement marking, signage, and truck maneuver as within-subject factors. Bicyclist velocity, lateral position, and acceleration were analyzed separately as the dependent variables. Mauchly's sphericity test was used to confirm sphericity assumptions. Mauchly's test examines the hypothesis that the variances of the differences between levels of independent variables are significantly different. Mauchly's test should be nonsignificant to assume that the condition of sphericity has been met. A significance level of 0.05 was adopted. Pairwise comparisons of estimated marginal means 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.

Whenever a significant effect was observed, profiles of the data for all of the subjects were plotted to visualize bicyclist behavior around loading zones. To visualize the bicyclist performance, a VBA platform was first created to automatically aggregate data every 2 meters. The aggregated data were then plotted along with means and standard deviations. R was used to visualize the data.

4.2.1 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 truck was present at the loading zone and no engineering treatment was applied around the conflict area (white lane markings without any warning sign) ($M_{Velocity}$ = 5.66 m/s, $SD_{Velocity}$ = 0.83 m/s). Participants encountering an exiting truck while bicycling on a solid green bike lane without a warning sign had the lowest mean velocity ($M_{Velocity}$ = 3.94 m/s, $SD_{Velocity}$ = 0.92 m/s).

Table 4.4 Mean and standard deviation of velocity (m/s) at each level of each independent variable

Truck Maneuver	Descriptive Statistics	White Lane Markings		Solid Green		Dashed Green	
		No Sign	Warning Sign	No Sign	Warning Sign	No Sign	Warning Sign
No Truck	M (SD)	5.66 (0.83)	5.62 (0.98)	5.30 (1.19)	5.57 (0.80)	5.58 (0.89)	5.55 (0.88)
Truck Parked	M (SD)	5.24 (1.12)	5.38 (1.07)	5.17 (1.01)	5.05 (1.22)	5.40 (0.87)	5.21 (0.99)
Truck Exiting	M (SD)	4.28 (1.35)	3.98 (0.75)	3.94 (0.92)	4.04 (0.73)	4.05 (0.74)	4.10 (1.09)

Repeated-measures ANOVA tests were used to determine the effects of factors on mean bicyclist velocity. Pairwise comparisons were also conducted to find the origin of difference whenever a significant effect was observed.

As shown in table 4.5, the factors of pavement marking ($F(2, 94) = 3.333$, $P = 0.050$) and truck maneuver ($F(2, 94) = 163.810$, $P < 0.001$) had significant effects on bicyclist velocity. No significant effect was observed for signage or either of the two- and three-way interactions. In terms of independent variables, truck maneuver had the highest effect on bicyclist velocity, with about 78 percent of within-subject variance being accounted for by truck maneuver.

Table 4.5 Repeated-measures ANOVA results on velocity (m/s)

Source	$F(v_1,v_2)$	P	η_p^2
Within-Subject Factors			
Pavement Marking	3.330 (2, 94)*	0.050	0.066
Signage	0.216 (1, 47)	0.644	0.005
Truck Maneuver	163.810 (2, 94)*	< 0.001	0.777
Pavement Marking × Signage	1.854 (2, 94)	0.162	0.038
Pavement Marking × Truck Maneuver	0.513 (4, 188)	0.698	0.011
Signage × Truck Maneuver	0.699 (2, 94)	0.470	0.015
Pavement Marking × Signage × Truck Maneuver	2.467 (4, 188)	0.069	0.050

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

Pairwise comparison analysis showed that when a truck was exiting, a bicyclist on a solid green pavement marking had a significantly lower velocity than that with white lane markings ($P = 0.050$). Figure 4.2 plots velocity distribution, aggregated at each 2 meters, for white lane and solid green lane markings, while a truck was exiting the loading zone. In this figure, and similar subsequent figures, the x-axis represents travelled distance along the bike lane, with the beginning of the loading zone as the 0 position. The positioning of parked vehicles, arrow marking, warning sign, pavement marking, and the truck (parked or exiting) is consistent with the tested environment. The data from each participant are plotted every 2 meters (small red dots). In addition, mean (large blue dot) and standard deviation (blue bars) values at each 2 meters are overlaid on the participants' data. As shown in figure 4.2, employment of a solid green pavement marking in the conflict area also resulted in a reduction in variability of velocity for all 48 participants.

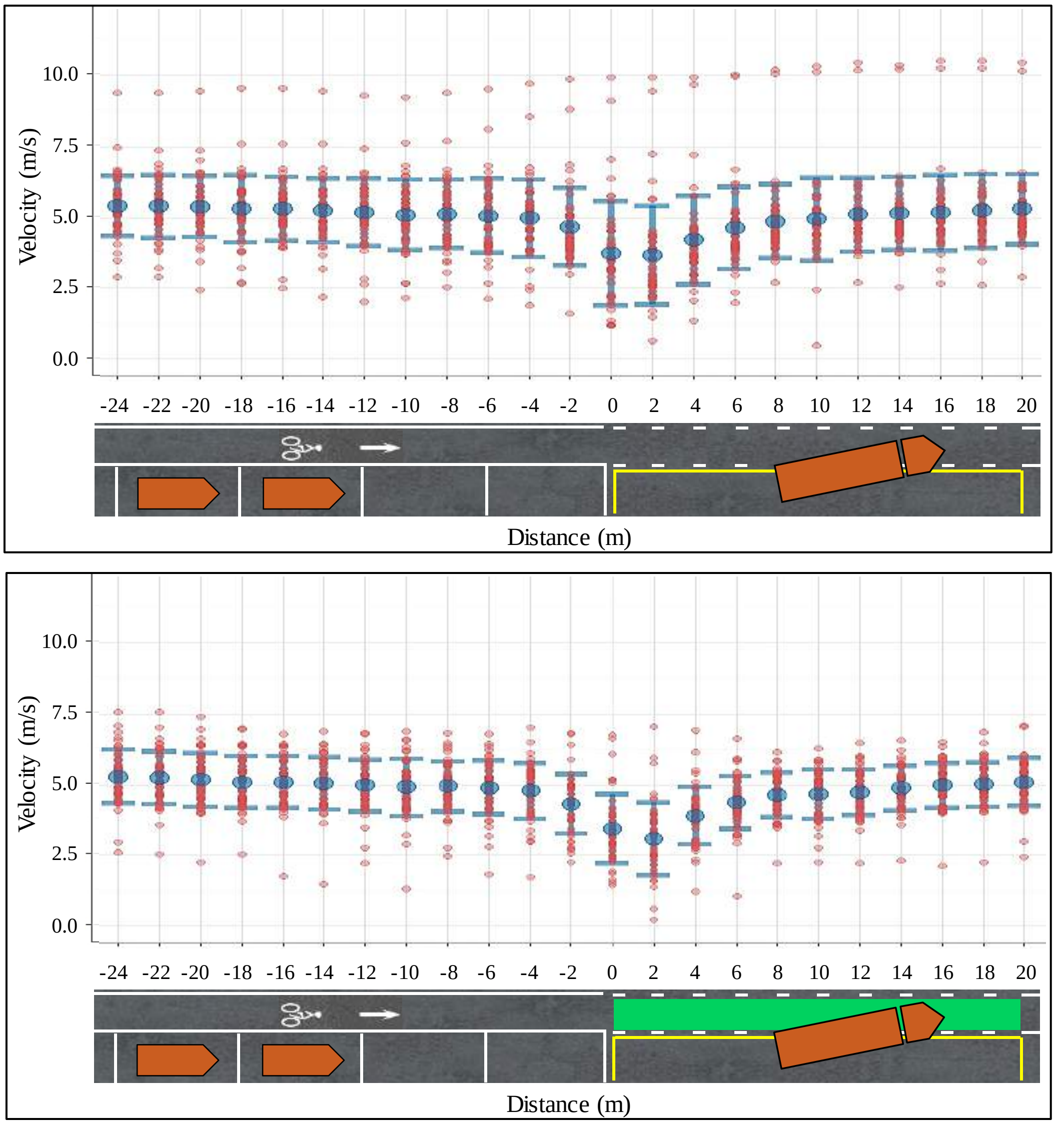


Figure 4.2 Effects of pavement markings on velocity at truck exiting

Pairwise comparison analysis showed that when white lane markings were applied in conflict areas, with and without a warning sign, all levels of truck maneuver had a significant effect on mean velocity ($P < 0.001$ for all pairwise comparisons). Figure 4.3 plots velocity distribution, aggregated at each 2 meters, for white lane markings without a warning sign and under different levels of truck maneuver. As shown on this figure, truck maneuver had a decreasing effect on mean velocity, with truck exiting having the lowest mean velocity. When solid green was applied, a statistically significant difference was observed for all levels of truck maneuver when a warning sign was present at the conflict area ($P < 0.001$ for all pairwise comparisons) and between an exiting truck and parked truck ($P < 0.001$) and no truck ($P < 0.001$) conditions without a warning sign. A similar distribution was observed for dashed green bike lanes. Because of the similarity in velocity distribution, data were visualized only for white lane markings without a warning sign (figure 4.3).

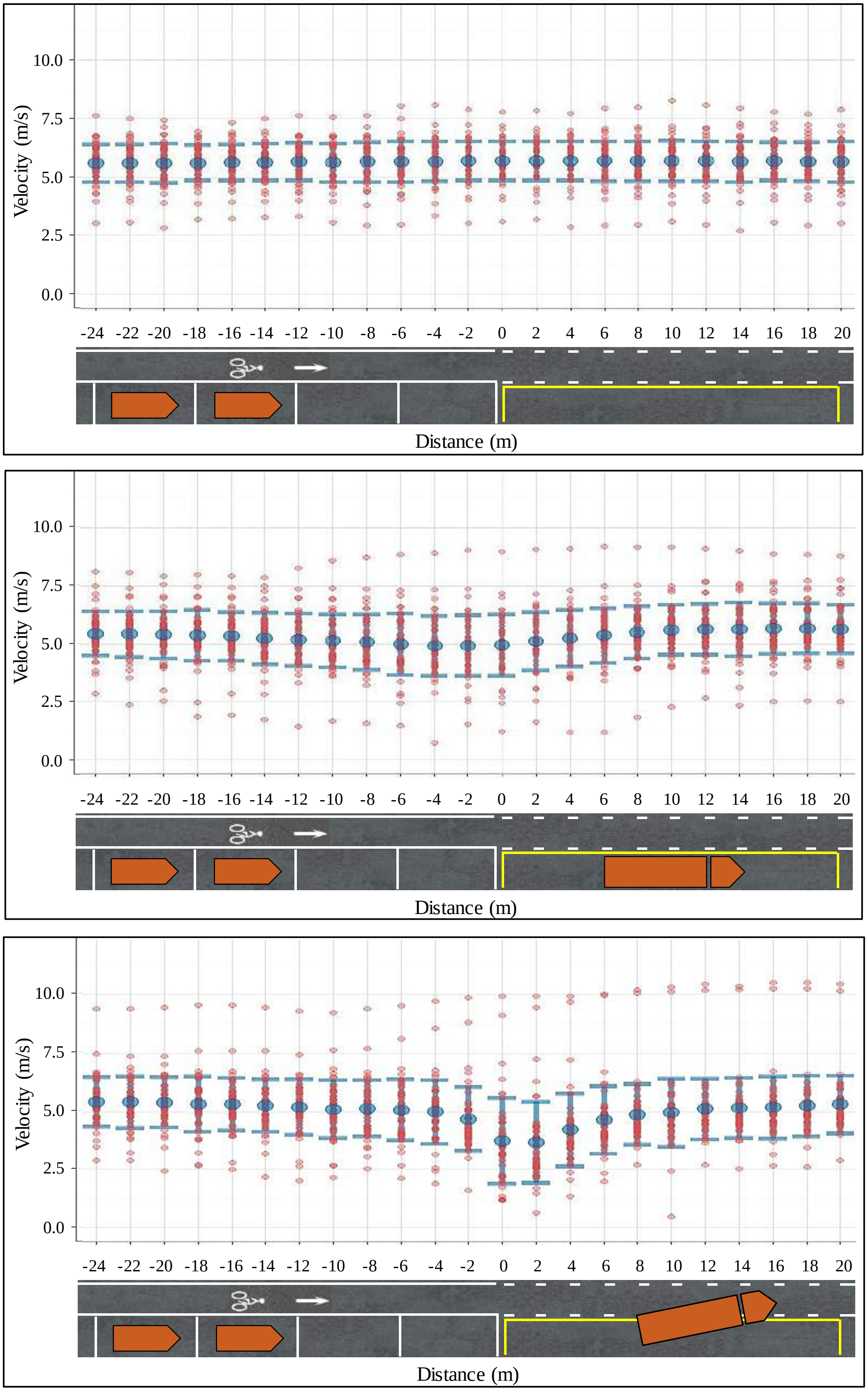


Figure 4.3 Effects of truck maneuvers on velocity at white lane markings

4.2.2 Lateral Position

The mean (M) and standard deviation (SD) values for the lateral position for each independent variable level are reported in table 4.6. The bike lane's right edge was defined as 0 m, making the left edge 1.83 m. Bicyclists had the least divergence from the bike lane's right edge when no truck was present in the loading zone, no colored pavement marking was used (only white lane marking), and a warning sign was placed near the conflict area ($M_{Lateral}$ = 0.59 m, $SD_{Lateral}$ = 0.15 m). However, participants encountering a parked truck while in a bike lane with white edge markings and a warning sign had the most divergence from the right edge of the bike lane ($M_{Lateral}$ = 1.20 m, $SD_{Lateral}$ = 0.73 m).

Table 4.6 Mean and standard deviation of the lateral position (m) at the independent variable level

Truck Maneuver	**Descriptive Statistics**	**White Lane Markings**		**Solid Green**		**Dashed Green**	
		No Sign	**Warning Sign**	**No Sign**	**Warning Sign**	**No Sign**	**Warning Sign**
No Truck	M (SD)	0.63 (0.13)	0.59 (0.15)	0.62 (0.29)	0.65 (0.29)	0.63 (0.21)	0.62 (0.16)
Truck Parked	M (SD)	1.08 (0.56)	1.20 (0.73)	0.97 (0.55)	1.11 (0.70)	1.08 (0.61)	1.02 (0.50)
Truck Exiting	M (SD)	1.05 (0.61)	1.00 (0.60)	0.87 (0.43)	0.91 (0.57)	0.92 (0.61)	1.06 (0.72)

Repeated-measures ANOVA tests were used to determine the effects of factors on mean bicyclist lateral position. Pairwise comparisons were also conducted to find the origin of difference whenever a significant effect was observed.

As shown in table 4.7, pavement marking ($F(2, 94) = 5.678$, $P = 0.005$), signage ($F(1, 47) = 4.805$, $P = 0.033$), and truck maneuver ($F(2, 94) = 31.491$, $P < 0.001$) had significant effects on bicyclist lateral position. There was also a statistically significant interaction between the combined effects of pavement marking and truck maneuver on bicyclist lateral position (F(4, 188) = 4.066, P = 0.008). In terms of independent variables, truck maneuver had the highest effect on bicyclist lateral position, with about 40 percent of within-subject variance being accounted for by truck maneuver.

Table 4.7 Repeated-measures ANOVA results on lateral position

Source	$F(v_1,v_2)$	P	η_p^2
Within-Subject Factors			
Pavement Marking	5.678 (2, 94)*	0.005	0.108
Signage	4.805 (1, 47)*	0.033	0.093
Truck Maneuver	31.491 (2, 94)*	< 0.001	0.401
Pavement Marking × Signage	1.671 (2, 94)	0.194	0.034
Pavement Marking × Truck Maneuver	4.066 (4, 188)*	0.008	0.080
Signage × Truck Maneuver	1.249 (2, 94)	0.288	0.026
Pavement Marking × Signage × Truck Maneuver	1.942 (4, 188)	0.105	0.040

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

Two-way interactions were also considered in the pairwise comparison for both pavement marking and truck maneuver. Figure 4.4 plots the lateral position estimated marginal means at each level of pavement marking and truck maneuver. As shown by this figure, the effects of pavement marking on lateral position were only apparent when a truck was present in the loading zone (either parked or exiting).

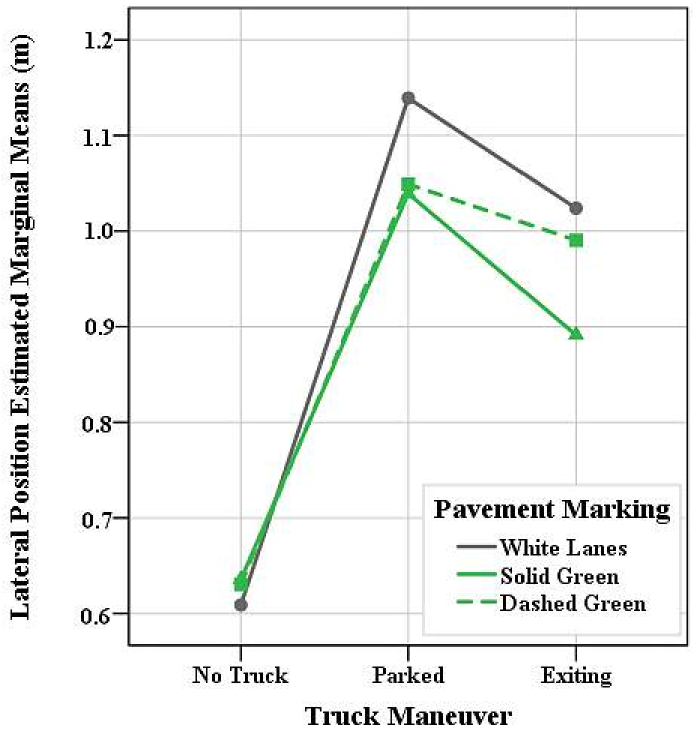


Figure 4.4 Statistically significant two-way interactions on lateral position, according to ANOVA.

Regardless of signage, pairwise comparisons showed that lateral position was significantly different for white lane marking and solid green bike lanes when a truck was parked in the loading zone ($P = 0.030$), or when it was exiting ($P = 0.018$). Figure 4.5 and figure 4.6 plot lateral position distribution, aggregated at each 2 meters, for white lane markings and solid green, while a truck was parked and was exiting the loading zone, respectively. As shown in these figures, employment of solid green pavement markings in the conflict area also resulted in a reduction in variability of lateral position for all 48 participants. Because of the similarity in lateral position distribution, data were visualized only for conditions without a warning sign (figure 4.5 and figure 4.6)

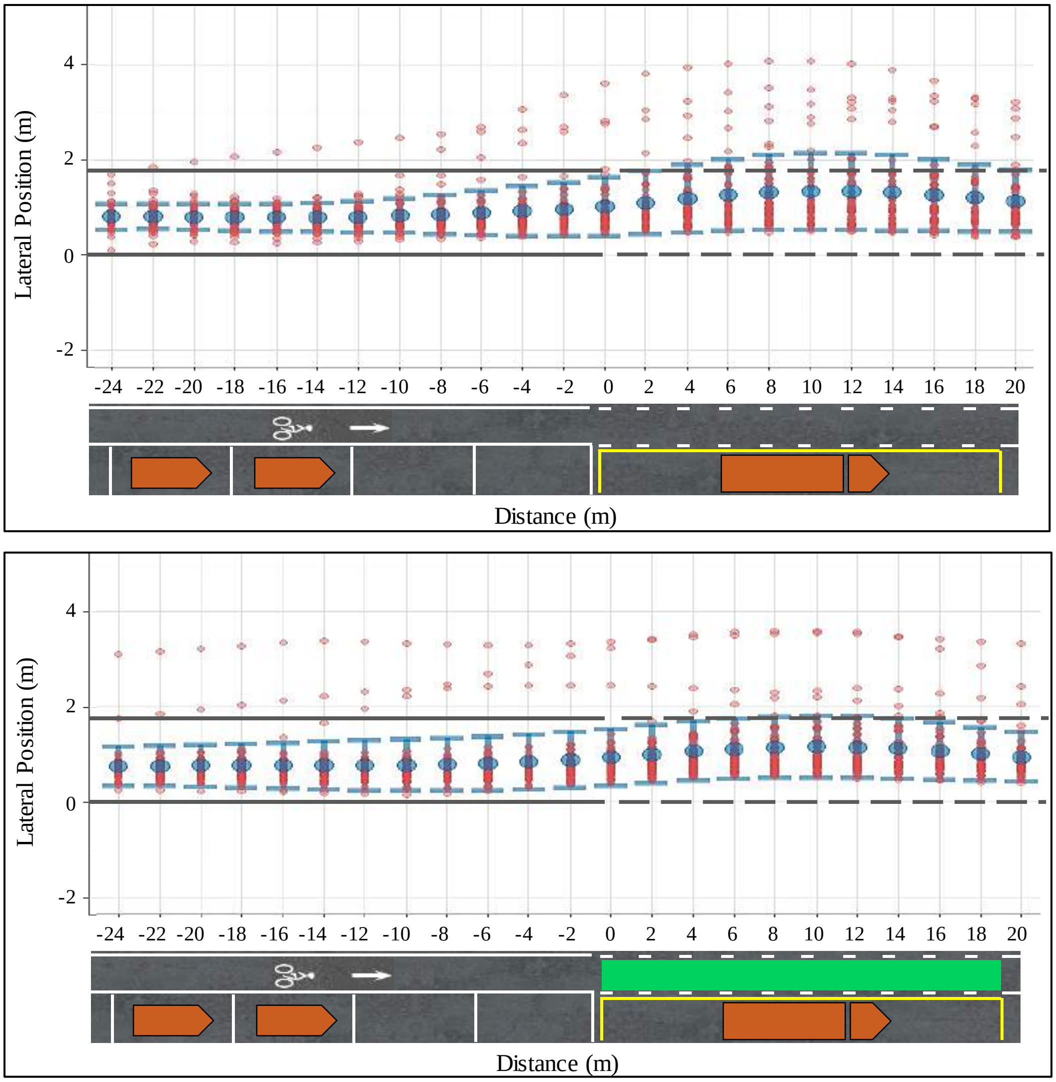


Figure 4.5 Effects of pavement markings on lateral position at truck parked

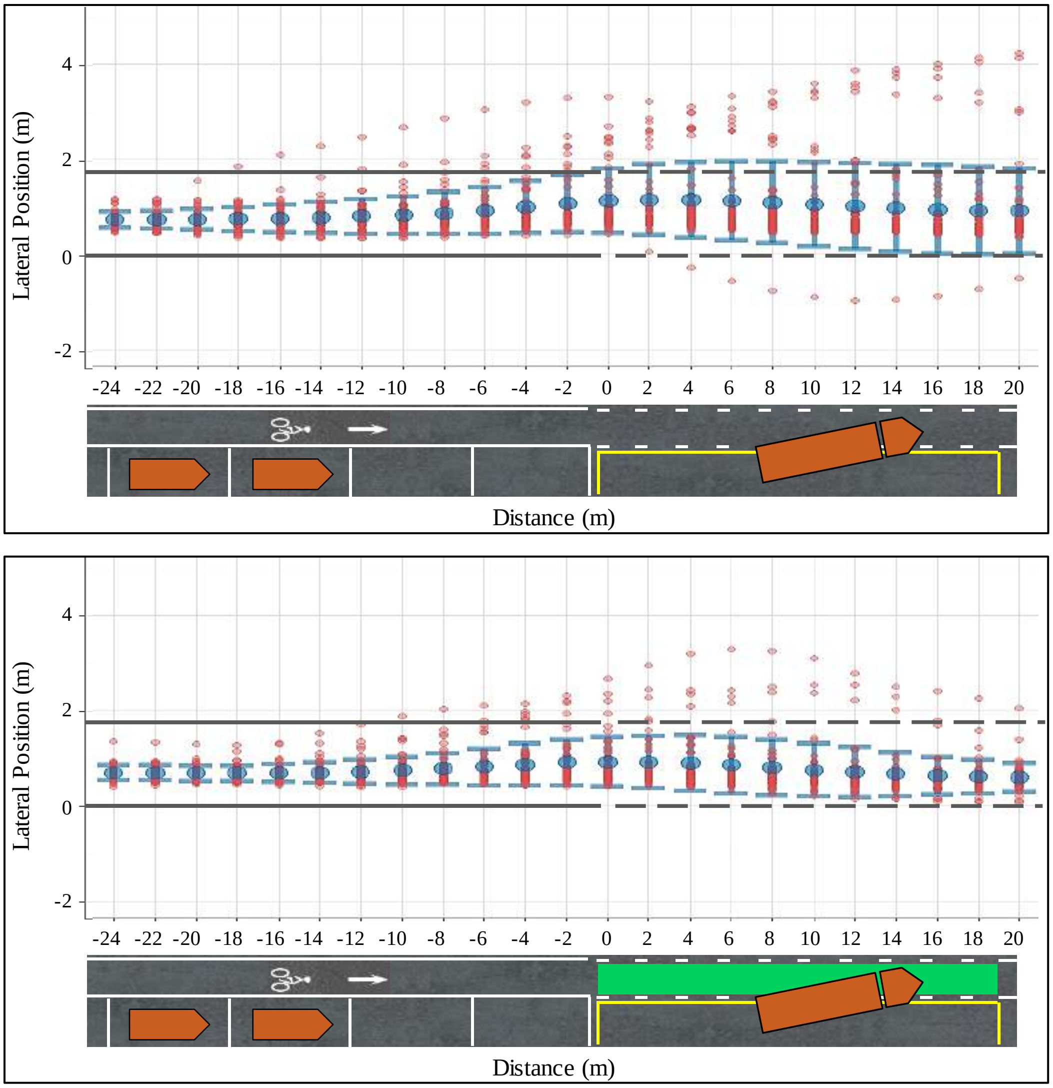


Figure 4.6 Effects of pavement markings on lateral position at truck exiting

As shown in table 4.7, a main effect was observed for signage. Pairwise comparison analysis showed that when a truck was parked, the presence of a warning sign was only significantly effective in conjunction with a solid green bike lane ($P = 0.050$). Figure 4.7 plots the lateral position distribution, aggregated at each 2 meters, for solid green pavement markings, with and without a warning sign. As shown in this figure, when a warning sign was used, bicyclists moved toward the left edge of bike lane and into travel lane. The implementation of a warning sign also resulted in an increase in lateral position variability for all 48 participants.

Further pairwise comparisons showed that when a truck was exiting the loading zone, a warning sign was only significantly effective in conjunction with dashed green bike lane markings ($P = 0.025$). Figure 4.8 plots the lateral position distribution, aggregated at each 2 meters, for dashed green pavement markings, with and without a warning sign. As shown on this figure, similar to the parked condition, when a warning sign was used, bicyclists shifted their position toward the left edge of bike lane and into travel lane. The employment of a warning sign also resulted in a significant increase in lateral position variability for all 48 participants. It was further observed that when a warning sign was used, bicyclists started to shift toward travel farther upstream of the loading zone.

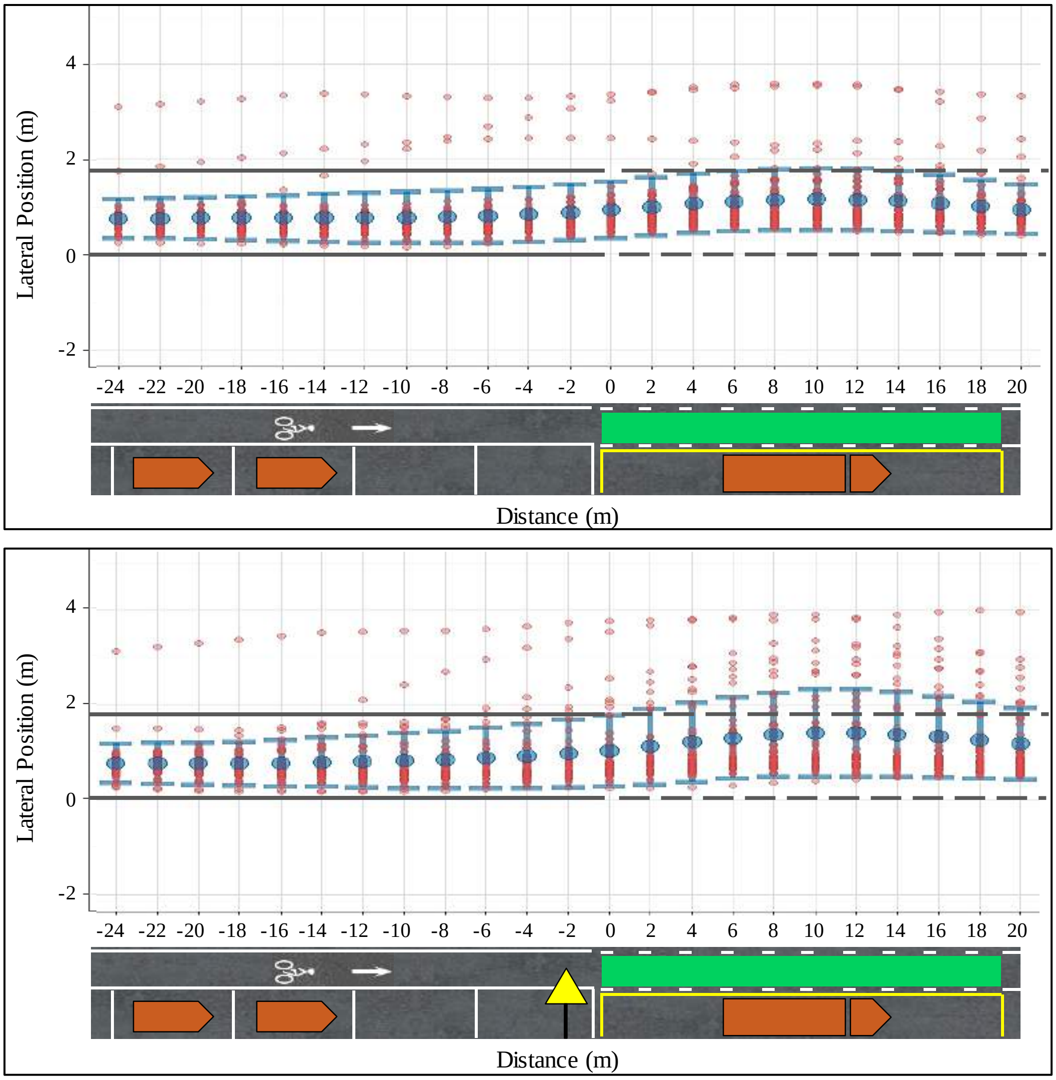


Figure 4.7 Effects of a warning sign on lateral position at truck parked

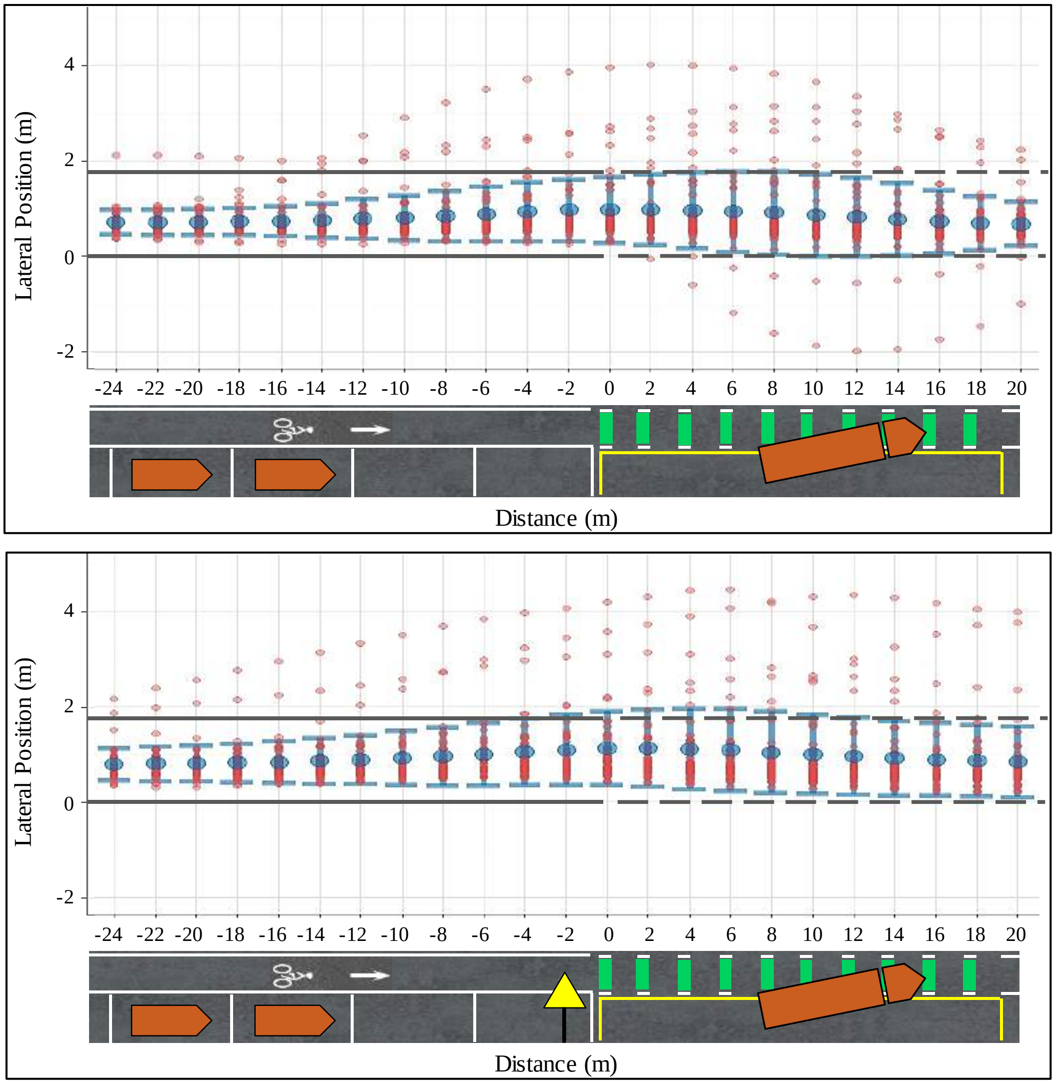


Figure 4.8 Effects of a warning sign on lateral position at truck exiting

As shown in table 4.7, a main effect was observed for the truck maneuver. With no warning sign in place, pairwise comparison analysis showed that when dashed green pavement markings were applied in conflict areas, all levels of truck maneuver had a significant effect on mean lateral position ($P < 0.001$ for no truck compared to parked truck, $P = 0.001$ for no truck compared to exiting truck, and $P = 0.004$ for parked truck compared to exiting truck). Figure 4.9 plots the lateral position distribution, aggregated at each 2 meters, for dashed green pavement markings without a warning sign and for different truck maneuvers. As shown in this figure, truck maneuver had an increasing effect on mean lateral position, with a parked truck having the highest divergence from the right edge of the bike lane. With a warning sign in place, pairwise comparison analysis showed that when a solid green pavement marking was applied in conflict areas, all levels of truck maneuver had a significant effect on mean lateral position ($P < 0.001$ for all pairwise comparisons). At all the levels of other factors, the difference in lateral position was only observed between the no truck condition and the parked truck condition (either parked or exiting). Because of the similarity in lateral position distribution, data were visualized only for dashed green pavement markings without a warning sign (figure 4.9).

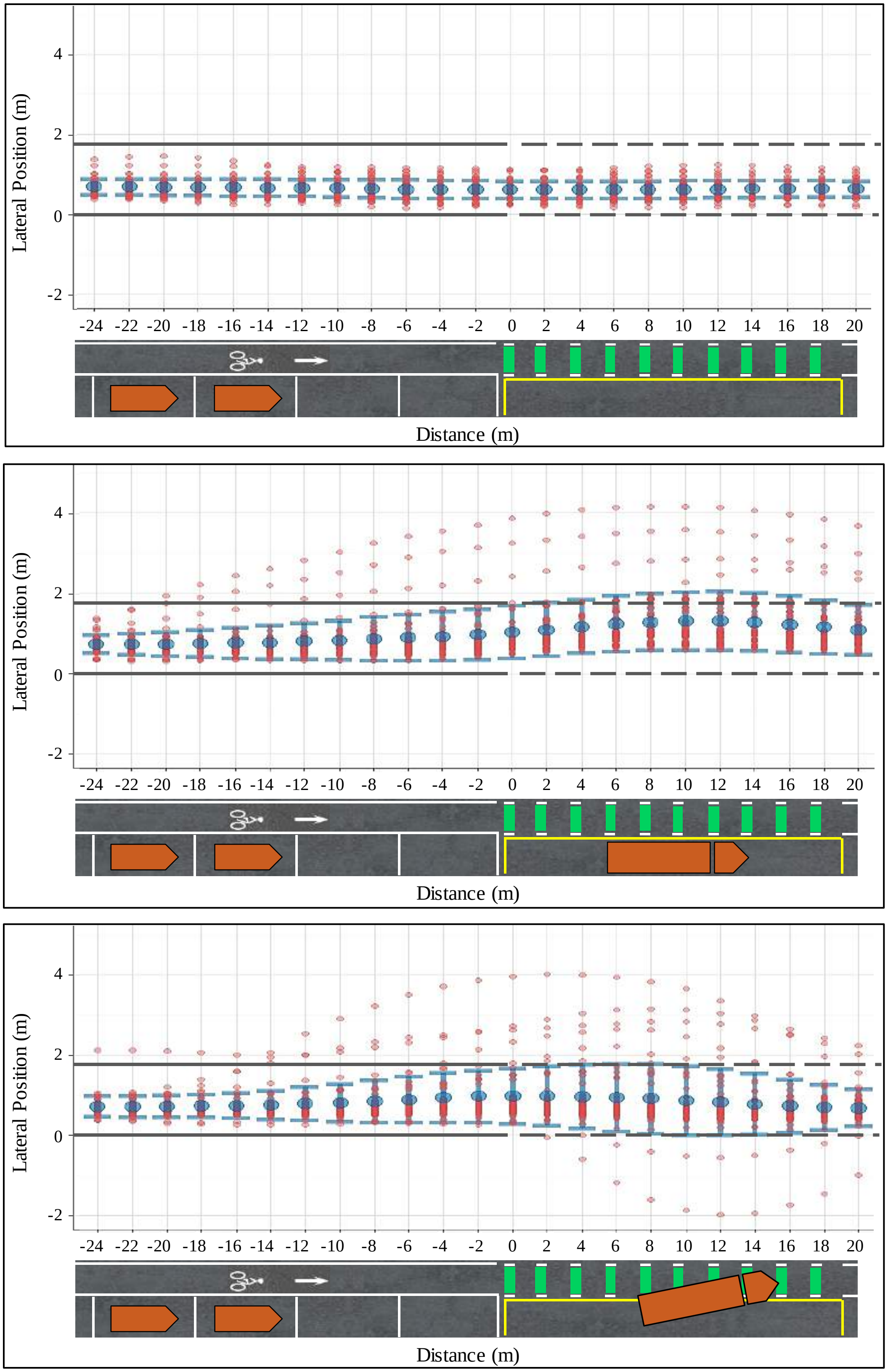


Figure 4.9 Effects of truck maneuver on lateral position with dashed green pavement markings

4.2.3 Acceleration / Deceleration

The mean (M) and standard deviation (SD) values for acceleration (+) and deceleration (-) at each independent variable level are reported in table 4.8. Bicyclists had the highest acceleration when no truck was present in the loading zone, no colored pavement marking was used (only white lane marking) and a warning sign was placed upstream of the conflict area ($M_{Acceleration} = 3.2 \times 10^{-4}$ m/s^2, $SD_{Acceleration} = 2.4 \times 10^{-4}$ m/s^2). Participants encountering an exiting truck while bicycling on a solid green pavement marking without a warning sign in place had the highest deceleration ($M_{Deceleration} = -2.0 \times 10^{-4}$ m/s^2, $SD_{Deceleration} = 7.6 \times 10^{-4}$ m/s^2).

Table 4.8 Mean and standard deviation of acceleration (+) and deceleration (-) (m/s^2) at each level of each independent variable

Truck Maneuver	Descriptive Statistics	White Lane Markings		Solid Green		Dashed Green	
		No Sign	Warning Sign	No Sign	Warning Sign	No Sign	Warning Sign
No Truck	M (SD)	2.3×10^{-5} (2.0×10^{-4})	-2.5×10^{-5} (2.5×10^{-4})	2.5×10^{-4} (2.0×10^{-4})	3.2×10^{-4} (2.4×10^{-4})	-3.3×10^{-5} (2.0×10^{-4})	-1.9×10^{-5} (2.1×10^{-4})
Truck Parked	M (SD)	-6.1×10^{-5} (4.0×10^{-4})	-1.2×10^{-4} (3.8×10^{-4})	1.4×10^{-5} (6.2×10^{-4})	1.9×10^{-5} (5.4×10^{-4})	-6.9×10^{-6} (3.3×10^{-4})	-3.2×10^{-5} (3.0×10^{-4})
Truck Exiting	M (SD)	-1.4×10^{-4} (5.0×10^{-4})	2.4×10^{-5} (4.7×10^{-4})	-2.0×10^{-4} (7.6×10^{-4})	-8.7×10^{-5} (6.0×10^{-4})	-2.0×10^{-5} (4.7×10^{-4})	2.2×10^{-5} (7.8×10^{-4})

Repeated-measures ANOVA tests were used to determine the effects on mean bicyclist acceleration. Pairwise comparisons were also conducted to find the origin of difference whenever a significant effect was observed.

As shown in table 4.9, the factors of pavement marking ($F(2, 94) = 3.342$, $P = 0.040$), and truck maneuver ($F(2, 94) = 10.470$, $P < 0.001$) had significant effects on bicyclist acceleration. There was also a statistically significant interaction between the combined effects of pavement marking and truck maneuver on bicyclist acceleration ($F(4, 188) = 6.783$, $P <$

0.001). In terms of the independent variables, truck maneuver had the highest effect on bicyclist acceleration, with about 18 percent of within-subject variance being accounted for by truck maneuver.

Table 4.9 Repeated-measures ANOVA results on acceleration / deceleration

Source	***F*(v_1,v_2)**	***P***	η_p^2
Within-Subject Factors			
Pavement Marking	3.342 (2, 94)*	0.040	0.066
Warning Sign	1.137 (1, 47)	0.292	0.024
Truck Maneuver	10.470 (2, 94)*	< 0.001	0.182
Pavement Marking × Warning Sign	0.322 (2, 94)	0.725	0.007
Pavement Marking × Truck Maneuver	6.783 (4, 188)*	< 0.001	0.126
Warning Sign × Truck Maneuver	2.011 (2, 94)	0.140	0.041
Pavement Marking × Warning Sign × Truck Maneuver	0.410 (4, 188)	0.801	0.009

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

Two-way interactions were considered to expand upon the pairwise comparison. Figure 4.10 plots the acceleration estimated marginal means at each level of pavement marking and truck maneuver. As shown by this figure, the effect of pavement marking on acceleration only happened when no truck was present in the loading zone. Since the focus of this study was on bike-truck conflicts, the pairwise comparison was not further evaluated for three levels of pavement marking.

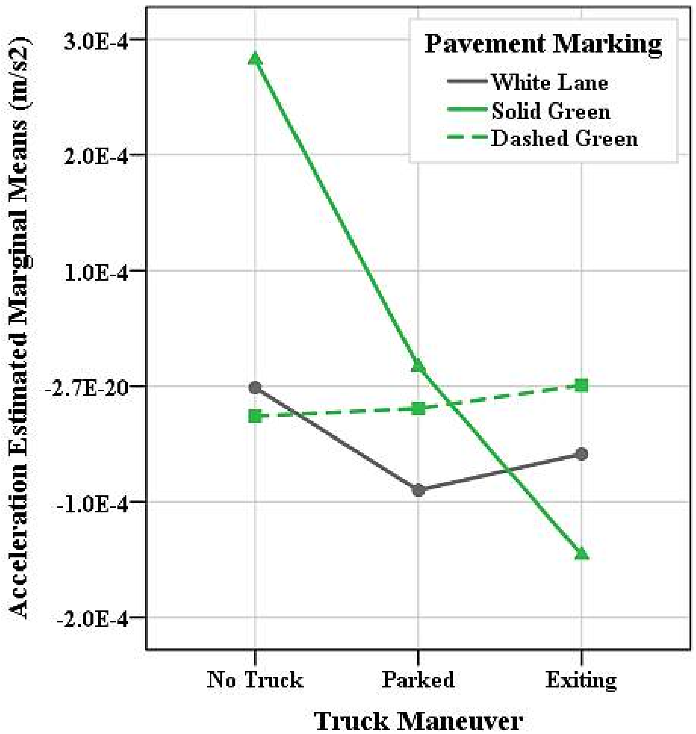


Figure 4.10 Statistically significant two-way interactions on acceleration, according to ANOVA.

As shown in table 4.9 and figure 4.10, a main effect was observed for truck maneuver. With no warning sign in place, pairwise comparison analysis showed that when the solid green pavement marking was applied in conflict areas, bicyclists had a significantly lower acceleration rate when a truck was parked ($P = 0.012$), and a significantly lower acceleration (deceleration in this case) when a truck was exiting ($P < 0.001$). Figure 4.11 plots acceleration distribution, aggregated at each 2 meters, for solid green pavement markings without a warning sign and under different levels of truck maneuver. As shown in this figure, a parked truck had an increasing effect on mean acceleration, and exiting truck has an increasing effect on deceleration. Another significant effect occurred between the no truck condition with a truck exiting under white bike lane markings ($P = 0.049$). With a warning sign in place, pairwise comparison analysis showed that when a solid green pavement marking was applied in conflict areas, bicyclists had a significantly lower acceleration rate when a truck was parked ($P = 0.009$), and a significantly lower acceleration (deceleration in this case) when a truck was exiting ($P = 0.001$). Because of the similarity in acceleration distribution, data were visualized only for solid green pavement markings without a warning sign (figure 4.11).

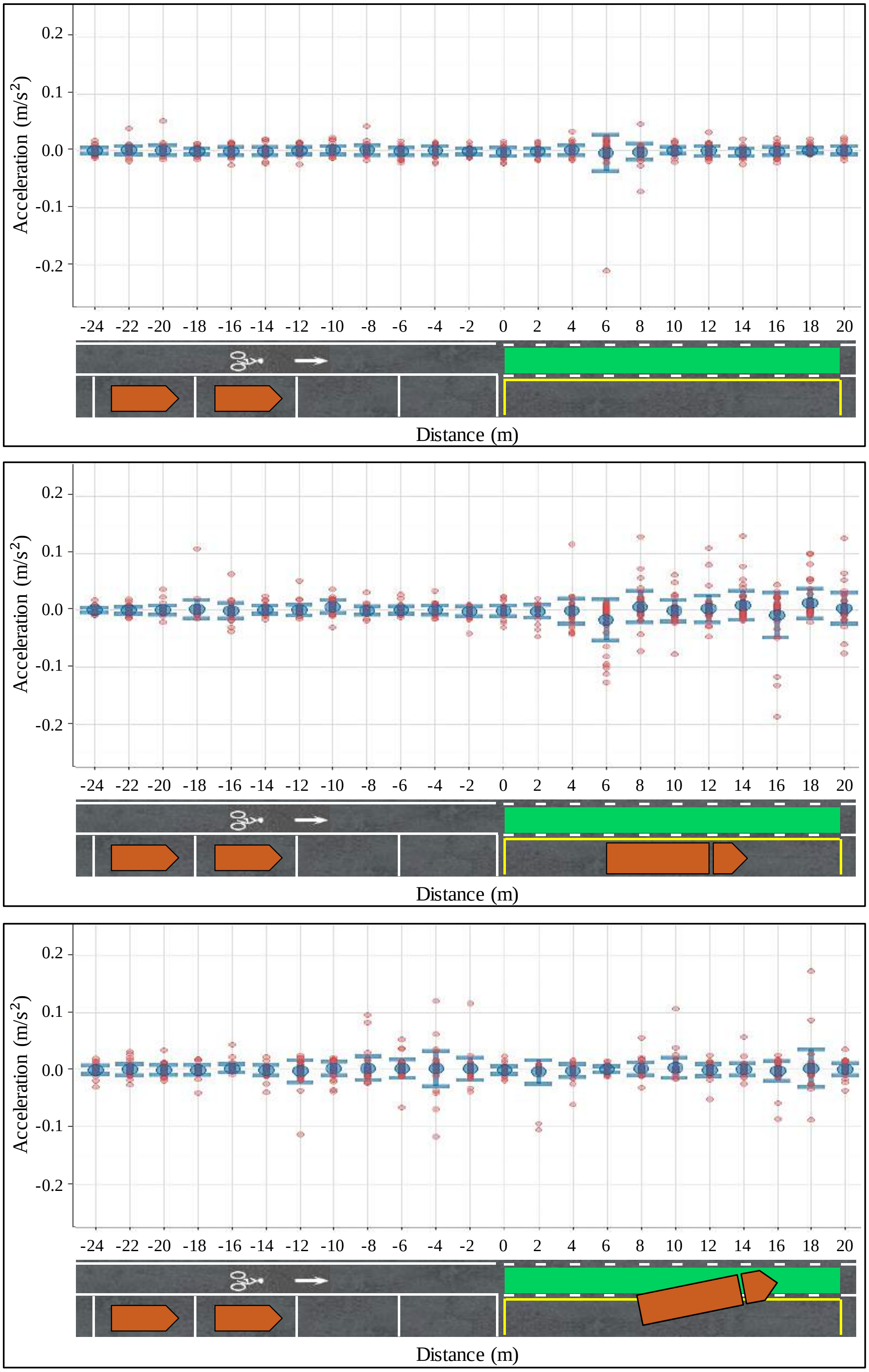


Figure 4.11 Effects of truck maneuver on acceleration at solid green

4.2.4 Selected Events

From the 288 total simulated conflicts between bicyclists and an exiting truck, four crashes were observed. These occurred when a bicyclist attempted to overtake the exiting truck. Data were analyzed to identify the bicyclist behavior in terms of velocity, lateral position, and acceleration in each of these four events.

Table 4.10 summarizes the characteristics of the three bicyclists who were involved in the observed bike-truck crashes. One of the participants was involved in two crashes. All bicyclists were among the younger portion of participants who used their bicycle on a daily basis to commute to school or work.

Table 4.10 Characteristics of bicyclists with crashes

Case	Age	Gender	Bicycling Frequency	Riding Purpose	Riding Duration	Crash Experience	Downtown Experience
1	19	Female	Daily	Commute to School/work	Less than 10 minutes	No	Yes
2 and 3	24	Male	Daily	Commute to School/work	10-20 minutes	No	Yes
4	24	Male	Daily	Commute to School/work	10-20 minutes	Yes	Yes

Figures 4.12 through 4.15 show captures from the simulated environment in these four cases. Case A happened when s solid green pavement marking was used in conjunction with s warning sign. Case B occurred when white lane markings were used with no warning sign in place. Case C happened when a dashed green pavement marking was used in conjunction with a warning sign. Case D occurred when white lane markings were used with no warning sign.

Table 4.11 summarizes the bicyclists' performances in terms of velocity, lateral position, and acceleration during crash events and compares them to the mean values of those metrics. In all cases, in response to the simulated truck maneuver, bicyclists decided not to stop or slow down but to pedal faster (high acceleration), increase their speed, and move toward the center of the travel lane to overtake the truck.

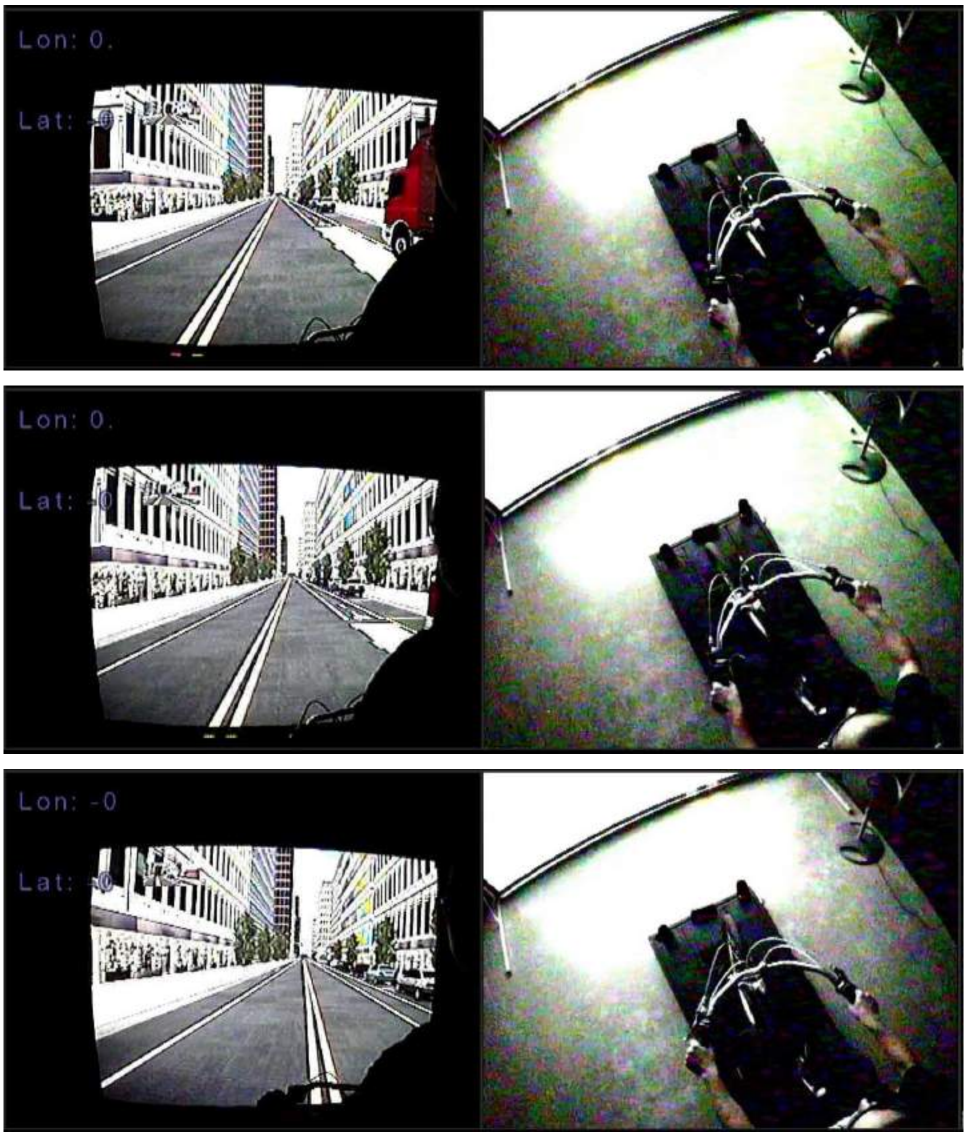


Figure 4.12 Crash event A observed in the simulated environment

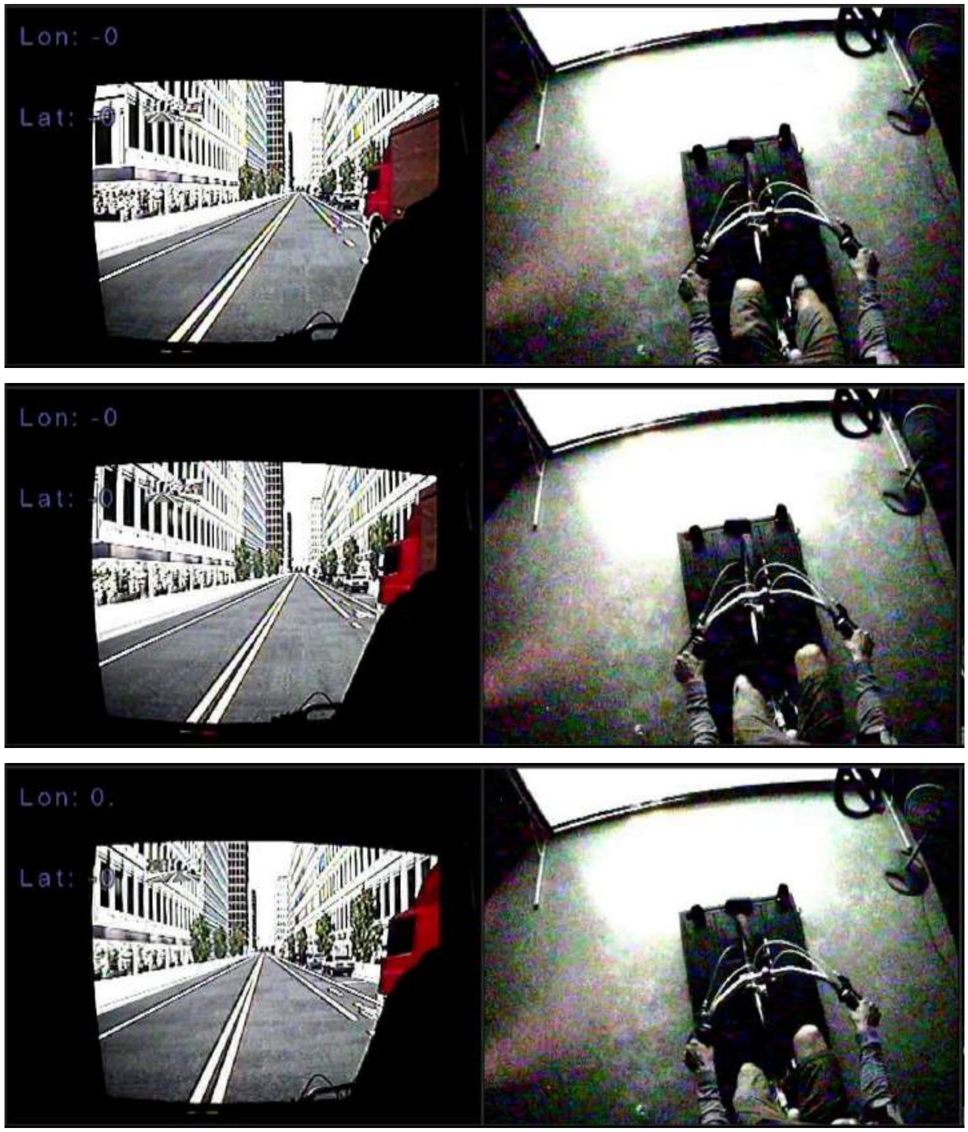


Figure 4.13 Crash event B observed in the simulated environment

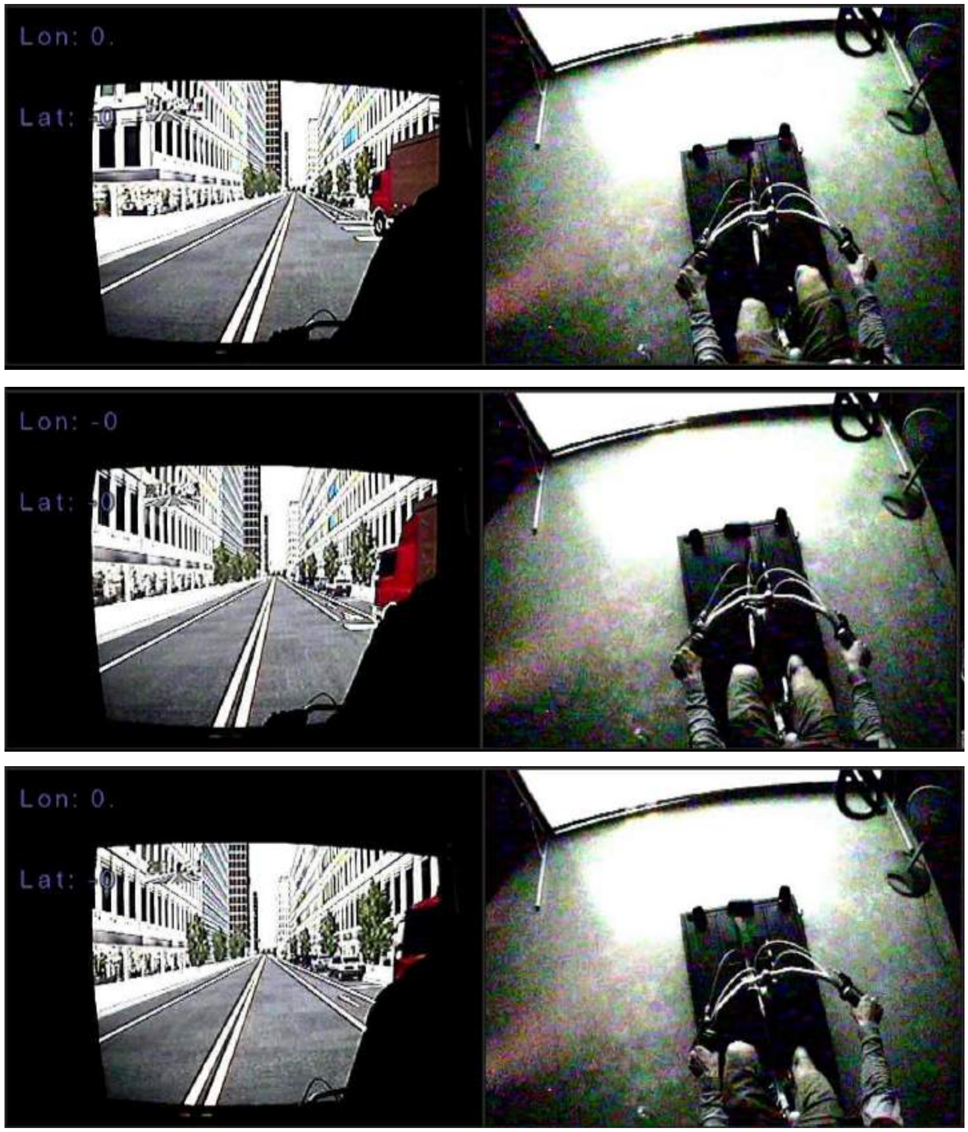


Figure 4.14 Crash event C observed in the simulated environment

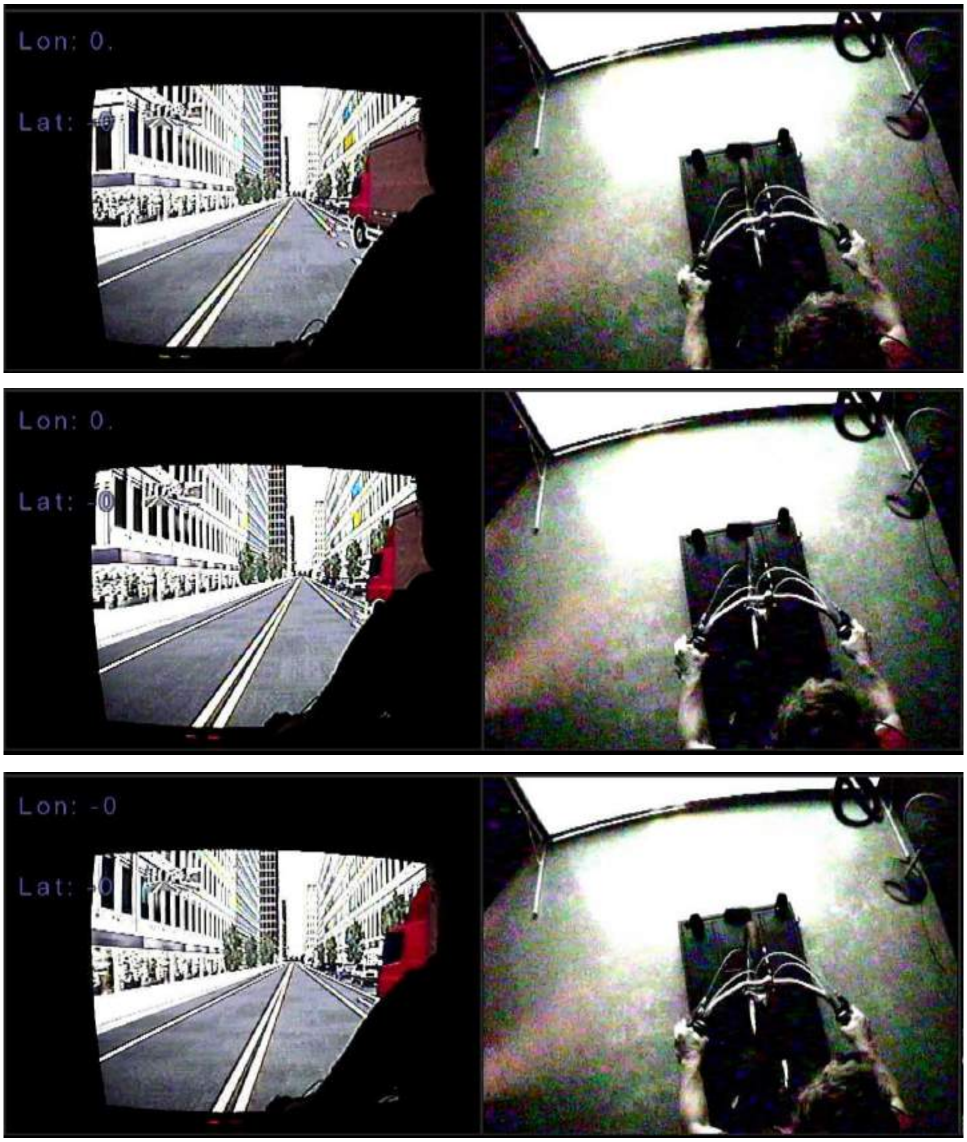


Figure 4.15 Crash event D observed in the simulated environment

Table 4.11 Bicyclists' performance during bike-truck crash events

Performance Measurement	Case A	Case B	Case C	Case D
Max Velocity at the Selected Event (m/s)	7.58	10.61	11.12	10.32
Mean Velocity at the Selected Event (m/s)	6.33	10.02	10.55	10.09
Mean Velocity for the Entire Dataset (m/s)	4.04	4.28	4.10	4.28
Max Lateral Position at the Selected Event (m)	5.35	4.17	4.33	4.26
Mean Lateral Position at the Selected Event (m)	4.03	3.14	3.00	3.40
Mean Lateral Position for the Entire Dataset (m)	0.91	1.05	1.06	1.05
Max Acceleration at the Selected Event (m/s^2)	0.064	0.071	0.123	0.110
Mean Acceleration at the Selected Event (m/s^2)	6.3×10^{-4}	0.001	0.006	0.001
Mean Acceleration for the Entire Dataset (m/s^2)	-8.7×10^{-5}	-1.4×10^{-4}	2.2×10^{-5}	-1.4×10^{-4}

5. Conclusions

This chapter presents study conclusions related to the interaction of bikes and trucks in the vicinity of commercial vehicle loading zones in urban areas. The first section summarizes the major findings of the experiment. The following sections discuss the limitations of this study and opportunities for future research related to bike-truck interaction.

5.1 <u>Findings</u>

The results of this study demonstrated a consistent narrative related to how bicyclists interact with trucks near urban loading zones and how different levels of engineering treatments are effective. Overall, the results showed that truck presence does have an effect on a bicyclist's performance, and this effect varies on the basis of the engineering treatments employed. There may be an increased risk of a crash associated with truck operations in urban loading zones, especially when no engineering treatment is used. The primary findings of this study include the following:

- *Pavement marking and truck maneuver had significant effects on bicyclist velocity.* When a truck was exiting the CVLZ, a bicyclist on a solid green pavement marking had a significantly lower velocity than a bicyclist on white lane markings. Truck maneuver had a decreasing effect on mean velocity, with a truck exiting the CVLZ causing the lowest mean velocity.
- *Pavement marking, signage, and truck maneuver had significant effects on bicyclist lateral position*. Lateral variability was significantly higher for white lane markings than for solid green bike lanes when a truck is parked or exiting the CVLZ. Under specific combinations of pavement marking and truck maneuver, the presence of a warning sign caused bicyclists to shift their position toward the left edge of bike lane and into the

adjacent travel lane. Truck maneuver had an increasing effect on mean lateral position, with a parked truck causing the highest divergence from the right edge of the bike lane.

- *Pavement marking and truck maneuver had significant effects on bicyclist acceleration*. The effect of pavement marking on acceleration only occurred when no truck was present in the CVLZ. A parked truck increased mean acceleration, and an exiting truck increased deceleration.

5.2 Recommendations

Depending on the desired bicyclist performance for approaching a CVLZ with a truck in it, different engineering treatments could be distinctly effective.

- *Velocity reduction:* Solid green pavement markings in the bicycle lane adjacent to the loading zone without a warning sign.
- *Lower divergence from the right edge:* Solid green pavement markings in the bicycle lane adjacent to the loading zone without a warning sign.
- *Higher divergence from the right edge:* White lane markings (no colored pavement markings in conflict area) with a warning sign in place.

5.3 Limitations

The following are the primary limitations of this project:

- A basic limitation of within-subject design is 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 duration of the test drives was 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 top left corner of the screen, providing a rear-view for bicyclists.
- The resource and time constraints of the project limited the number and levels of variables that could be evaluated. In particular, the truck maneuver was only analyzed with a 2.5-second cut-in time gap, and only conventional bike lanes were modeled.
- Although all the possible efforts were made to recruit a sample of bicyclists most similar to the bicyclist population in state of Oregon, the final sample was skewed in terms of age and education.

5.4 Future Work

Additional research is needed to continue to explore the critical safety issue of bike-truck interactions near urban loading zones and to extend the work of this study. The following are potential research threads that would augment this study and further expand the topic of how bicyclists interact with trucks in urban environments:

- This research studied pavement markings, signage, and truck maneuvers as the independent variables for bike-truck interactions. Many other variables could also be considered. For example, shorter cut-in time gaps, such as 1-second, could potentially provide a higher rate of crash and near miss events. Additionally, different forms of bike lanes, such as buffered bike lanes 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 make it possible to look at scenarios where bicyclists interact with a moving truck in the adjacent travel lane.
- Incorporate a wider range of truck sizes, traffic volume, and street speed variability.

- Using an instrumented bicycle experiment in an urban area could help validate the results of this study.

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Appendix A Traffic Signs for Bicycle Facilities

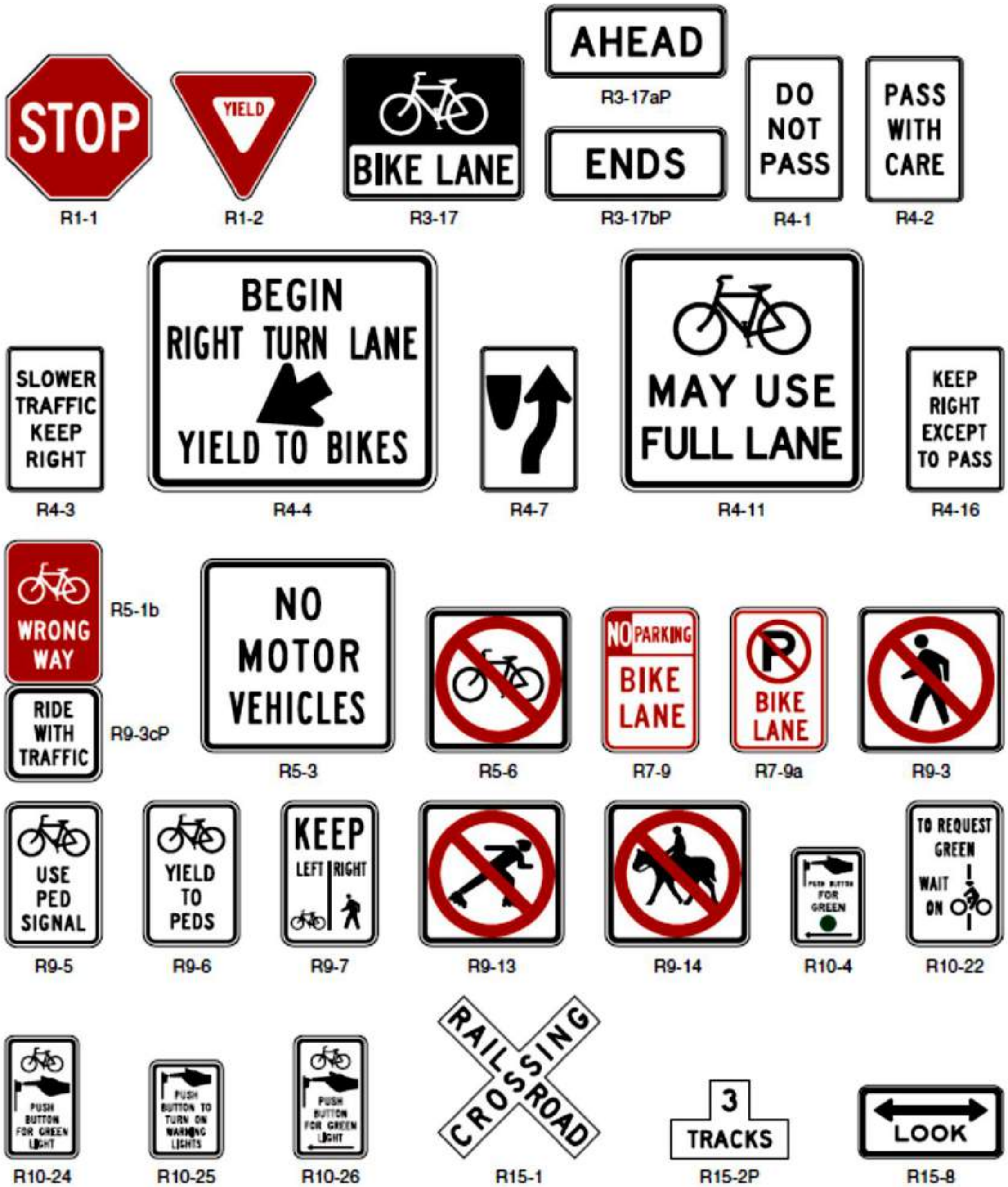

Figure A.1 Regulatory signs and plaques for bicycle facilities in the MUTCD (FHWA, 2009)

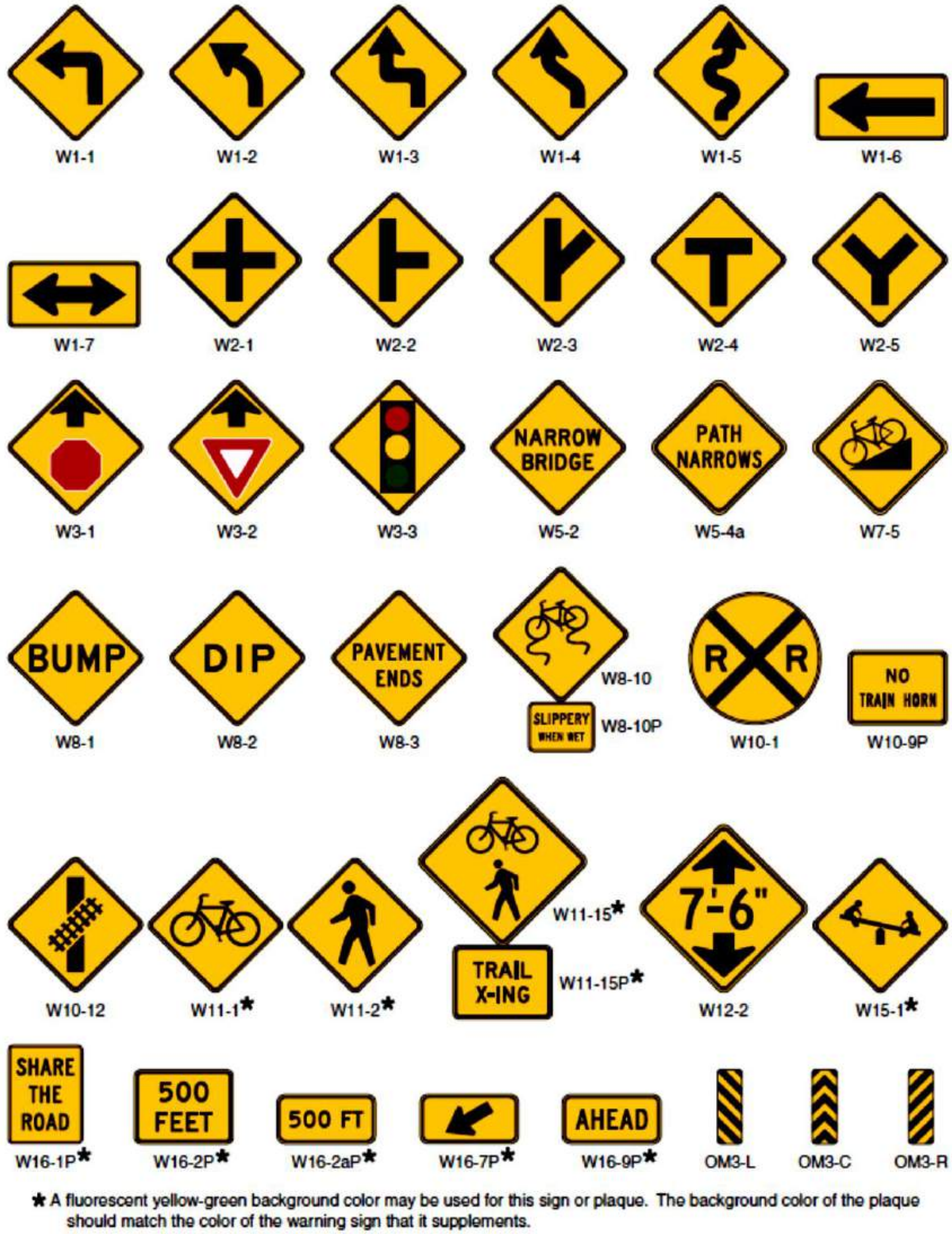

Figure A.2 Warning signs and plaques for bicycle facilities in the MUTCD (FHWA, 2009)

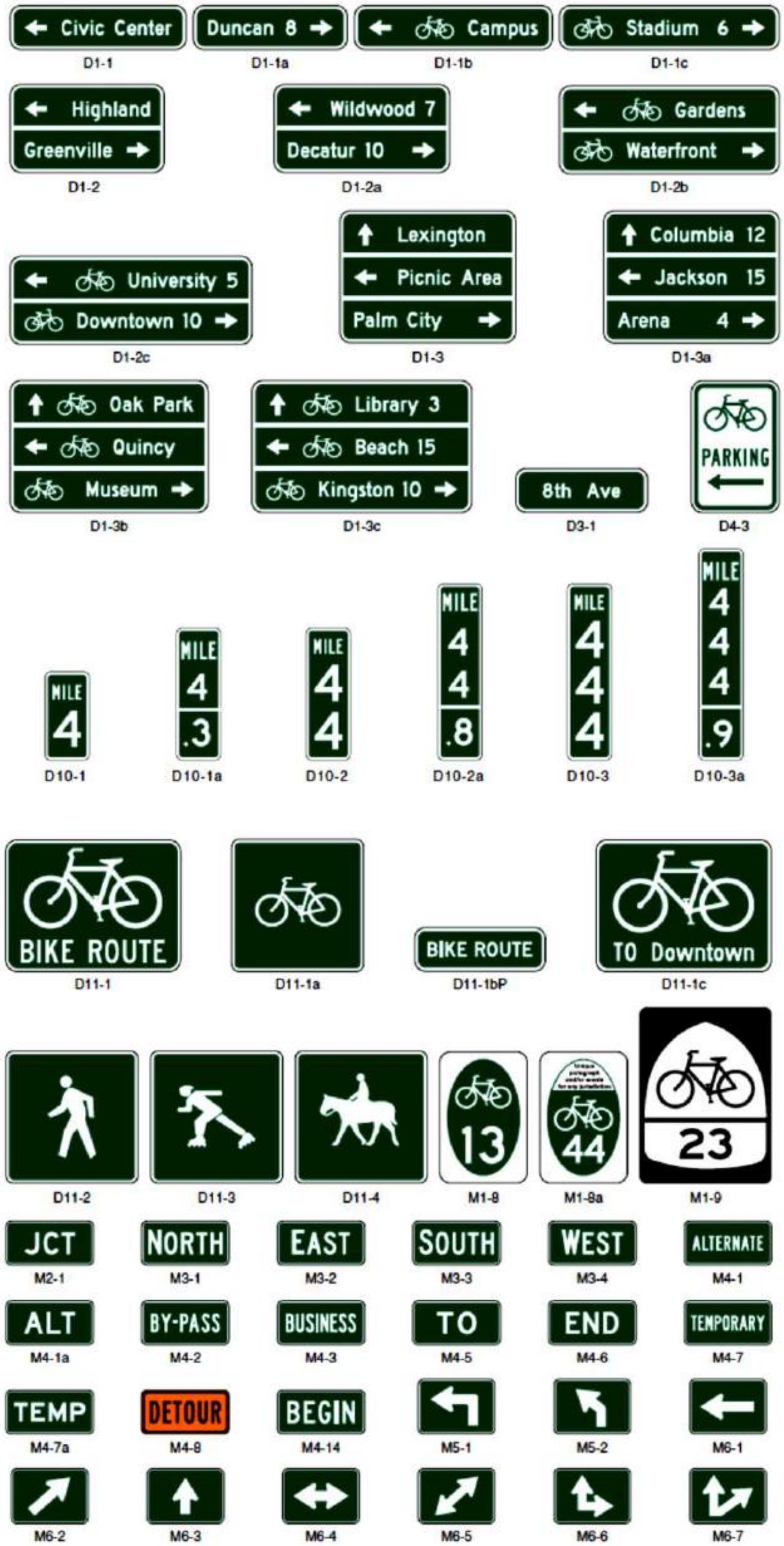

Figure A.3 Guide signs and plaques for bicycle facilities in the MUTCD (FHWA, 2009)