AN EVALUATION OF DOOR ZONE COLLISIONS BETWEEN BICYCLES AND VEHICLES

By:
Cadell Chand

A THESIS

submitted to

Oregon State University

University Honors College

in partial fulfilment of
the requirements for the
degree of

Honors Baccalaureate of Science in Civil Engineering
(Honors Scholar)

Presented May 29th, 2018
Commencement June 2018

AN ABSTRACT OF THE THESIS OF

Cadell Chand for the degree of Honors Baccalaureate of Science in Civil Engineering
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Title: AN EVALUATION OF DOOR ZONE COLLISIONS BETWEEN BICYCLES AND VEHICLES

Abstract approved:

David S. Hurwitz

The door zone can be defined as the area occupied by an open car door. Door zone collisions between bicycles and vehicles is common, however little information exists on the nature of this collision type. This study utilizes Oregon State University's Bicycling Simulator to examine bicyclist behavior in the door zone using performance measures of velocity and lateral position. Within-subject factors of time to the open door and effective bicycle lane width remaining with the vehicle door open were used. Eye-tracking data was also collected. The experiment was successfully completed by 21 participants. Two-way repeated measures ANOVA results indicate that time to the open door significantly influences bicyclist's velocity and lateral position when in close proximity to the door zone. A shorter time to the open door causes more bicyclists to depart the bicycle lane, and creates a greater spread between bicyclists who choose to decelerate or accelerate when in close proximity to the door zone. The data may also suggest a correlation between effective bicycle lane width and the bicyclist's decision to accelerate past an opening vehicle door. Additionally, the majority of bicyclists departed the bicycle lane when given only one foot of effective bicycle lane width.

Key Words: *door zone, bicycle simulator, effective bicycle lane, time to the open door, eye-tracking*
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Honors Baccalaureate of Science in Civil Engineering project of Cadell Chand
Presented on May 29th, 2018

APPROVED:

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request

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Cadell Chand, Author

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1 INTDRODUCTION

U.S. urban areas have seen an increase in bicyclists during the past decade as urban transportation systems further diversify into multiple modes to combat increasing traffic congestion. This shift is being met with rapid changes in infrastructure planning, design, operations, and maintenance. More accessible bicycle infrastructure has further increased the viability and popularity of bicycling, especially as means for commuting. Cities such as Amsterdam, Netherlands have had bicycle mode shares of nearly 50%, and Portland, Oregon has set a goal to achieve a bicycle mode share of at least 25% by 2030 (PBOT, 2010). Despite these shifts, bicycle crashes in the past decade have increased by nearly nine percent (Meng, 2012). This may be due to bicyclists and motor vehicles sharing more infrastructure, causing conflicts in certain situations due to the differences in the nature and dynamics of these modes (Meng, 2012). One conflicts of particular interest to this study is the door zone collision.

The door zone can be defined as the area which an open car door extends beyond the vehicle (Prinz, 2015). Bicycles commonly come in conflict with vehicle doors while riding adjacent to on-street parallel parking. This roadway cross section is found extensively in urban areas, or special cases such as roadways surrounding a university or stadium. Door zone collisions are not usually fatal, and are underreported as a result. Few engineering treatments exist to mitigate the occurrence or severity of door zone collisions. It is unclear whether existing engineering treatments, such as wider bicycle lanes or variations of parallel parking striping, are effective. Additionally, existing knowledge on the human factors in door zone collisions is limited.

This study aims to contribute to an understanding of how bicyclists behave in close proximity to the door zone, specifically targeting bicycle commuters in the Oregon State University (OSU) community. The OSU Bicycling Simulator will be used to examine how two within-subject variables (changes in time to the open door and changes in effective bicycle lane width) affect bicyclist's velocity and lateral position. Time to the open door is defined as the time from when the vehicle door is first detectable to the bicyclist, to when the bicyclist passes the vehicle door if that bicyclist were to travel at a constant velocity equal to its approach velocity. Effective bicycle lane width is defined as the width of the bicycle lane remaining unobstructed after the vehicle door is fully opened. The study also collected post-ride survey responses on participant's experiences and perceptions on door zone collisions, and eye-tracking data for future work.

2 LITERATURE REVIEW

This literature review explores past research on bicyclist behavior and bicycle collisions with vehicle doors. The first section defines the door zone and the door zone collision, as well as an overview on why it is of significant interest to roadway users and transportation safety professionals. The second section introduces basic concepts of bicycle behavior, both in general and when in close proximity to the door zone. The following section gives an overview of possible options for mitigating door zone collisions, as well as knowledge gaps on the topic as identified by the author. Last, this literature review includes an overview of the role of bicycling simulator laboratories in transportation safety research, and motivations for this study based on the findings of this literature review.

2.1 Door Zone

2.1.1 What is the Door Zone and Door Zone Collision?

Definitions of the door zone can vary slightly, however the generally accepted definition is the area which an open car door extends beyond the vehicle (Prinz, 2015). Apart from non-standard vehicle door designs, the standard vehicle door is about 45 inches wide and swings outward from the vehicle (Torbic, 2014). Therefore, a car door that is fully opened can increase the distance a vehicle extends beyond the curb by nearly four feet, creating the door zone. By deduction, a door zone collision is any collision that occurs within the door zone. Often, these collisions are between a vehicle and a bicyclist. Door zone collisions are commonly referred to as "getting doored" (Prinz, 2015). Figure 2.1 illustrates the door zone created by the open door of a 2012 Honda Civic adjacent to a 4-foot-wide bicycle lane. The width of a 2012 Honda Civic door is 45 inches (Honda, 2011). The door zone in Figure 2.1 extends approximately halfway into the bicycle lane, which is not uncommon.

Figure 2.1: Door Zone (in green) Created by 45” 2012 Honda Civic Door Along 4’ Bicycle Lane

Figure 2.2 illustrates the door zone with a cross section of a typical road layout where the bicycle lane is placed between the motor vehicle travel lane and an on-street parallel parking lane. Note the effective bicycle lane width when the vehicle door is opened compared to the marked bicycle lane width (Figure 2.2). This figure, developed by AASHTO, is commonly used in bicycle lane design guides. However, when the figure is compared with an overlay of more realistic road vehicle, and bicycle dimensions (Figure 2.3), the effective bicycle lane width is reduced to zero. In this case, the bicyclist is either forced into the motor vehicle travel lane to maneuver around the open vehicle door, or forced to stop until the door is closed, thereby removing it as an obstruction.

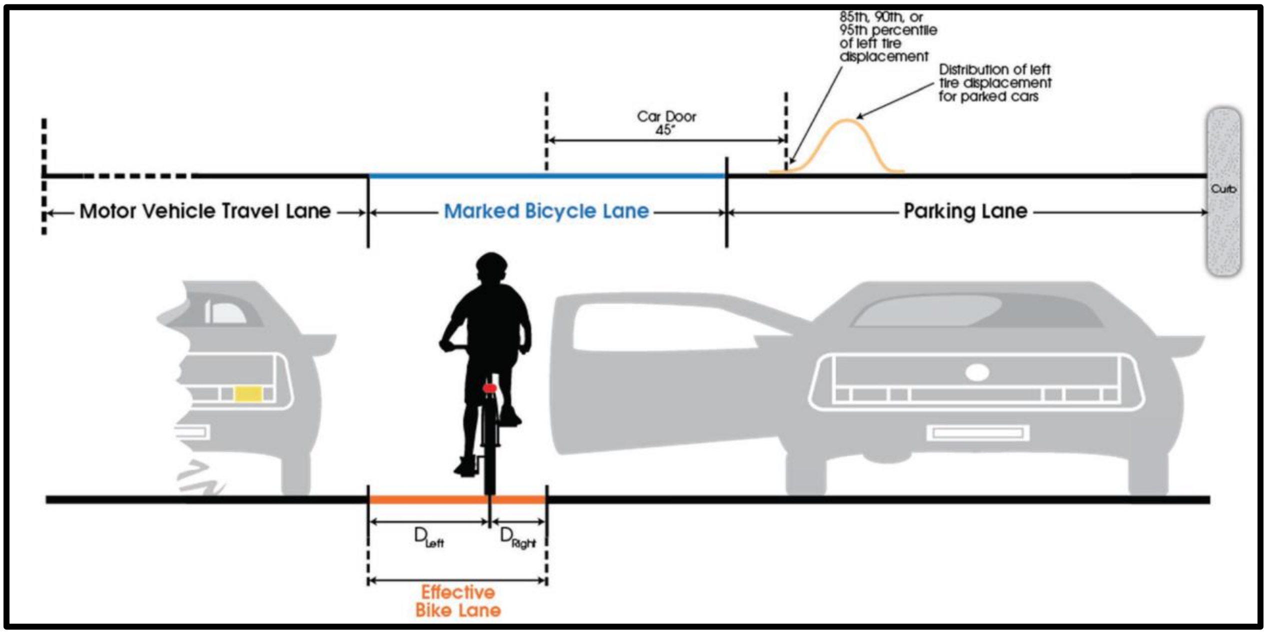


Figure 2.2: Ideal Roadway Cross-Section and Utilization with Bicycle Lane and On-Street Parallel Parking (Torbic, 2014)

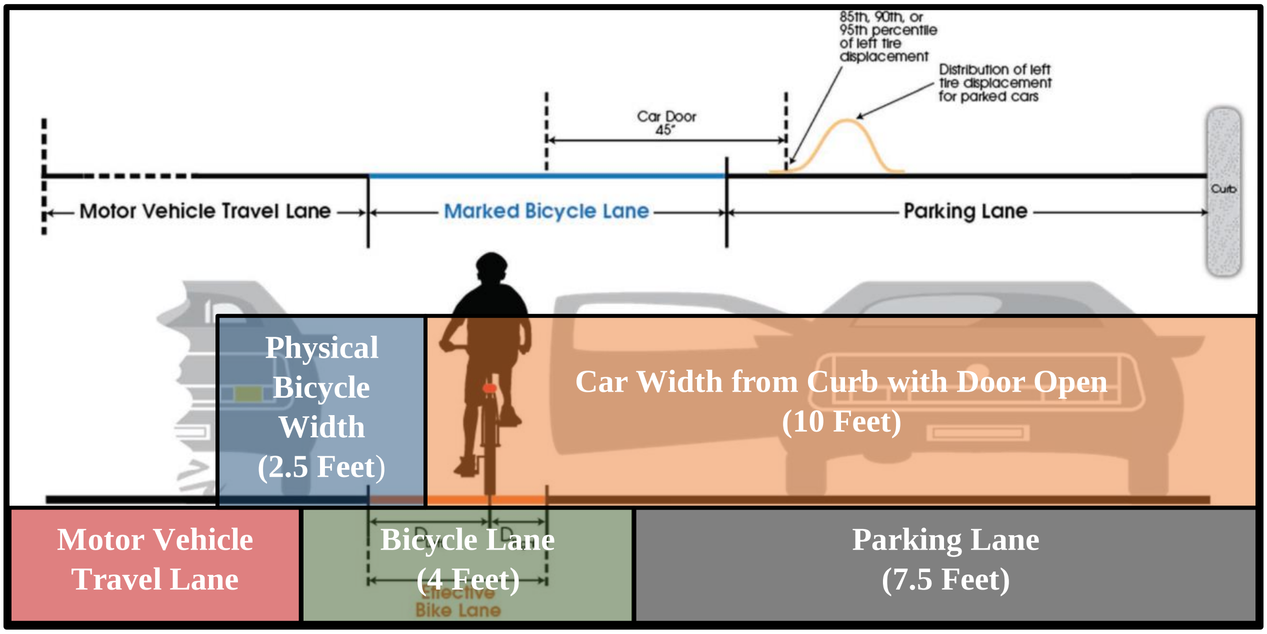


Figure 2.3: Actual Roadway Cross-Section and Utilization with Bicycle Lane and On-Street Parallel Parking (Torbic, 2014)

For roadways with a bicycle lane adjacent to on-street parallel parking, the 85th percentile of door zones will reach 10 feet from the curb (Houten, 2005). It is also worth noting that Figure 2.2 uses a bicycle's physical width, which is 2.5 feet (AASHTO, 2012). As seen in Figure 2.4, the minimum operating space of a bicycle is defined by AASHTO as 4 feet, while the preferred operating space is said to be 5 feet. Using these AASHTO values, the bicyclist will be forced further into the motor vehicle travel lane than what Figure 2.3 suggests in order to maneuver around an open vehicle door.

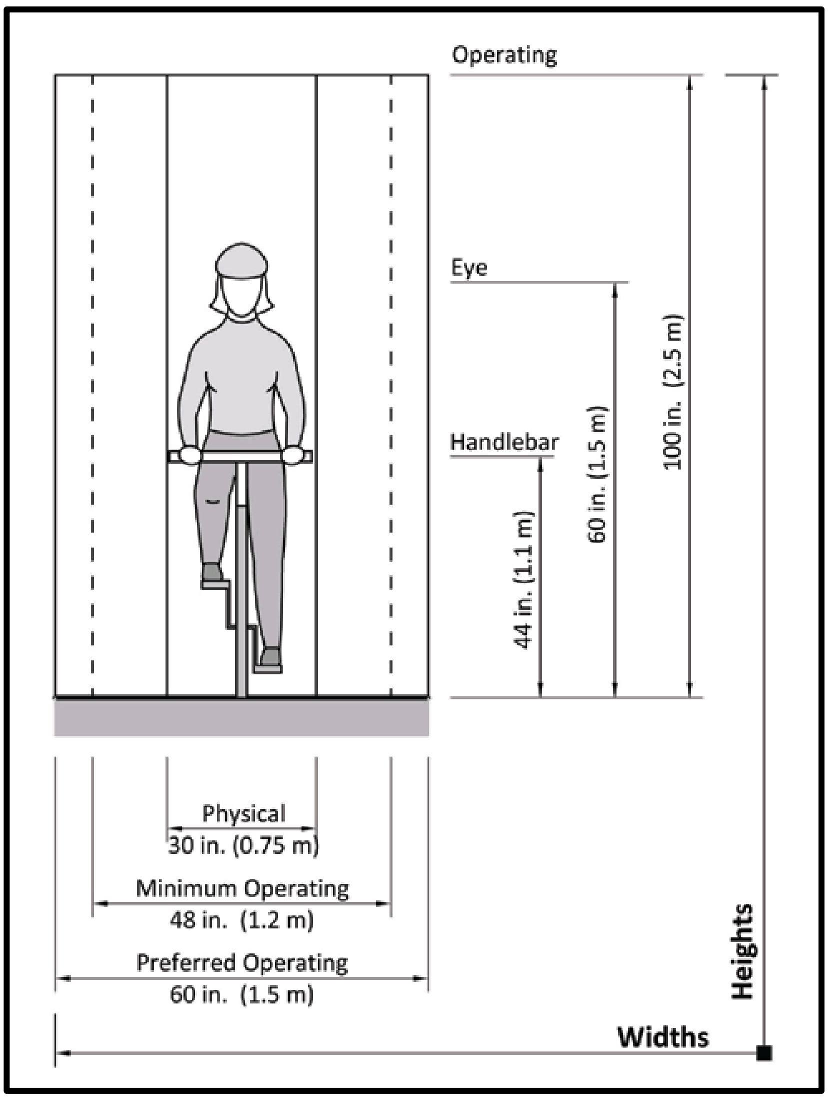


Figure 2.4: AASHTO Values for Bicycle Width (AASHTO, 2012)

The clear majority of bicycle lanes in the United States fall between widths of 4 and 5 feet, and the majority of registered vehicles in the United States have door widths of nearly 4 feet (Torbic, 2014). Using a physical bicycle width of 2.5 feet, Table 2.1 shows the lateral space a bicycle would have to escape the door zone in scenarios of varying car door widths and bicycle lane widths. The results of the table show that the only scenario which allows enough lateral space for a bicycle to pass involves a 6-foot-wide bicycle lane and a 3-foot-wide car door. This scenario is relatively unlikely, meaning the majority of bicycle infrastructure in the United States provides no safe option for a bicyclist to escape the door zone. Furthermore, these scenarios do not consider wider non-traditional bicycles, such as bicycles that are pulling trailers or adult tricycles.

Table 2.1: Lateral Space Remaining in the Bicycle Lane with Varying Bicycle Lane Widths and Car Door Widths

Width of Bicycle Lane (ft.)	**Car Door Width (ft.)**		
	3	**4**	**5**
6	3	2	1
5	2	1	0
4	1	0	-1

[a]*Assumes a bicycle width of 2.5 feet*
[b]*Unshaded – enough space for a bicycle to avoid the door zone within the bicycle lane*
[c]*Shaded – not enough space for a bicycle to avoid the door zone within the bicycle lane*

2.1.2 Why do Door Zone Collisions Occur?

While knowledge gaps currently exist on bicyclist behavior in close proximity to the door zone, some information does exist on driver and passenger behavior when opening a vehicle door. A cyclist who is riding just under 20 mph (a typical velocity for an adult cyclist on flat terrain) will move 5-6 car lengths in one second. So, if a driver or passenger looks away from oncoming traffic for one second or more before opening their door, an approaching bicycle riding just under 20 mph may easily go undetected by that driver or passenger (Cumming, 2012).

To check for oncoming traffic, many drivers will look in either their rearview mirror or side mirror before opening their door. Both strategies pose limitations that increase the chance of a bicyclist approaching undetected. The rearview mirror does not show the driver their blind spot, which will almost certainly lead to a door zone collision if a bicyclist is located inside of that blind spot when the door is opened. The side view mirror does not show the driver what is directly behind their vehicle. If parking spaces are empty, cyclists may ride closer to the curb inside those empty parking spaces to increase the distance between them and the motor vehicle lane (assuming that the bicycle lane is between a motor vehicle travel lane and on-street parallel parking). This means the cyclist will be approaching parked vehicles outside of the side mirror's view (Cumming, 2012). Beyond this, some drivers and passengers may not check for oncoming bicyclists at all before opening their vehicle door. To summarize these driver and passenger factors with other factors that contribute to the door zone collision, a Haddon Matrix was completed based on the information found from this literature review in Table 2.2. The physical environment is considered constant with time in this Haddon Matrix.

Table 2.2: Haddon Matrix Describing the Factors in a Door Zone Collision

<table>
<tr><th rowspan="2">PHASES</th><th colspan="4">FACTORS</th></tr>
<tr><th>Bicyclist</th><th>Driver</th><th>Physical Environment</th><th>Social Environment</th></tr>
<tr><td>Pre-Event</td><td>•Bicycling knowledge and experience
•Expectancy
•Visibility (e.g. reflective gear and lights)</td><td>•Level of caution
•Limited view
•Situational awareness
•Education to door zone collision avoidance</td><td rowspan="3">•Urban
•Parallel parking
•Bicycle lanes
•Lighting (utilities or daylight)
•Traffic volume and speed on travel lane adjacent to bicycle lane
•Other engineering treatments</td><td>•Bicycle density (strength in numbers)</td></tr>
<tr><td>Event</td><td>•Speed
•Braking ability
•Lateral position
•Failure of level 1, 2, or 3 situational awareness</td><td>•Impairment (DUI or Distraction)
•Failure of level 1, 2, or 3 situational awareness</td><td>•Community attitude towards liability and responsibility for safety</td></tr>
<tr><td>Post-Event</td><td>•Where bicyclist lands (e.g. into traffic)
•Safety equipment</td><td>•Damage to vehicle door
•Hit and run</td><td>•Official reporting of incident
•Repercussions for event</td></tr>
</table>

2.1.3 Why Are Door Zone Collisions Dangerous?

Door zone collisions began to garner attention after the death of Dana Laird in Cambridge, Massachusetts on July 2nd, 2002. This door zone collision was caused by the placement of bicycle lanes inside the door zone by the City of Cambridge (Goodridge, 2005). Increased risk of door zone related collisions due to poorly designed bicycle infrastructure, such as in Cambridge at the time, may encourage more bicyclists to ride on sidewalks (Anson, 2011). The rate of collisions is much higher when bicyclists ride on sidewalks with pedestrians versus on the road with motor vehicles because of the difference in mobility and braking ability between the modes.

In a study on perceived risk, focus groups were shown pictures of roads with different bicycle infrastructure layouts. The focus groups consistently spoke about the importance of riding outside of the door zone, and identified infrastructure that placed them outside of the door zone as something that would reduce their perceived risk of riding on that road (Sanders, 2013). Forty-four percent of focus group participants that identified as regular bicyclists stated that “getting doored” was always a worry they had while riding their bicycle. Eighty-three percent of focus group participants who rode daily reporting being hit by a car door at least once (Sanders, 2013). The study identified the perceived risk of being doored as one of the top barriers to bicycling in the United States, and found that regular cyclists worry much more about being doored than non-regular cyclists (Sanders, 2013). Figure 2.5 shows how door zone collisions have a greater ratio of hit to near miss incidents than all other bicycle collision types, with the exception of the cut-off collision type.

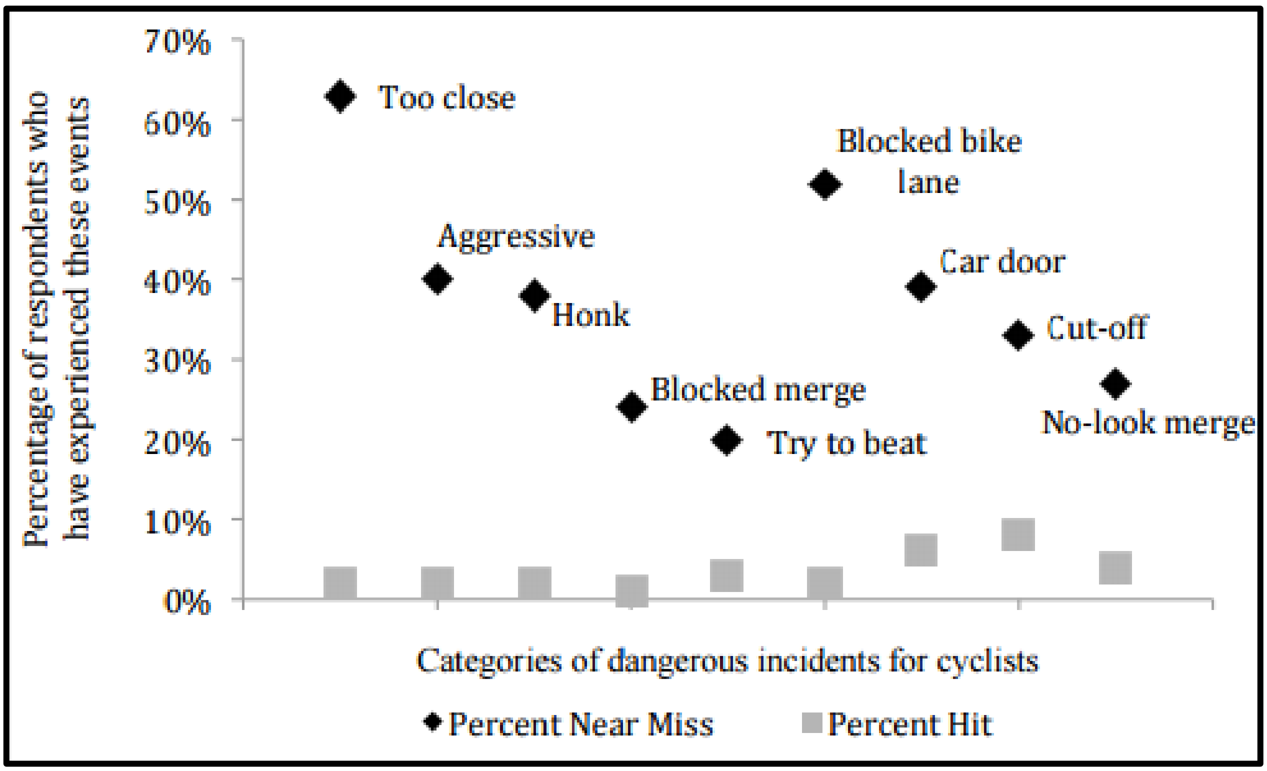


Figure 2.5: Ratio of Hit to Near Miss Bicycle Incidents for Varying Events (Sanders, 2013)

To avoid door zone collisions, bicyclists tend to take evasive maneuvers (Johnson, 2016). Such maneuvers may cause the bicycle to swerve into the adjacent motor vehicle travel lane, or the handlebar of the bicycle may strike the vehicle door and throw the rider off the bicycle. It is common for bicyclists to be thrown into the travel lane on their head or back. The vulnerable position this places the bicyclist in is especially dangerous when there is an approaching vehicle in the motor vehicle travel lane.

The attention bicyclists must allocate to avoid door zone collisions while riding adjacent to on-street parallel parking in addition to the short reaction time required avoid door zone collisions may prevent assessment of other potential hazards by the bicyclist. This includes pedestrians, hazards on the road's surface, and motor vehicle traffic in the adjacent lane (Johnson, 2016). To be sure to avoid potential conflicts with these hazards, cyclists may choose to travel at lower velocities (Johnson, 2016). Lower velocities may produce new problems, such as danger created by an increase in cyclists overtaking one another.

The door zone collision is a common type of collision, but is not normally tracked by transportation departments. Therefore, most statistical data related to the door zone collision are associated with small sample sizes. Currently, there is no statistical data available to completely quantify the problem of the door zone collision (Dixon, 2009). However, the small sample sizes of data available do give some idea of the severity and frequency of door zone collisions. In Toronto, Canada door zone collisions are the third most frequent cyclist collision (Johnson, 2016), and in London, United Kingdom eight percent of all cyclist deaths were caused by cyclists swerving to avoid car doors (Laker, 2012). The State of Illinois has data that suggests one in five officially reported bicycle collisions are door zone collisions (Dayton, 2016), while in Boston, Massachusetts one in six self-reported bicycle collisions are door zone collisions.

Additionally, the second most prevalent bicycle related collision with a response from emergency medical services in Boston, Massachusetts were bicycle collisions with vehicle doors (BDOT, 2013). This provides evidence that while door zone related collisions are not usually fatal, they can result in serious injuries. Data from medical services in Australia report that the body region most commonly injured by a door zone collision is the shoulder and cranium (Johnson, 2018).

The likelihood of door zone collisions increases in roadways with speed limits lower than 40 mph, one direction of motor vehicle travel, and roadways that use bicycle lanes (Pai, 2011). Roadways with these characteristics are most commonly found in urban areas. Door zone collisions increased eighty percent from 2008 to 2009, and may increase further as communities continue to urbanize (Johnson, 2016).

2.2 Bicyclist Behavior

2.2.1 Bicycle Kinematics and Dynamics

Bicycle sight distance is a function of bicyclist perception, brake reaction time, initial velocity, coefficient of friction between the roadway and bicycle tire, and braking ability of the bicycle (AASHTO, 2012). The equations for distance travelled during the brake reaction time and braking distance are found in Table 2.3. Both these equations show that braking ability becomes weaker exponentially as the velocity of the bicycle increases. However, cyclists tend to avoid collisions by braking rather than changing direction (Johnson, 2016). This means the door zone collision is a unique scenario in which the bicyclist may prefer to change direction instead of brake to avoid a collision with an open vehicle door. It is also important to note the special dynamics of bicycles that result from having two wheels. It is more difficult for a bicycle to change its direction at high velocities, however a bicycle must maintain some velocity to remain upright and stable. No work has been done to find the specific kinematic limits in which a bicycle is stable enough for the bicyclist to feel comfortable or be capable of operating and maneuvering the bicycle (Dozza et al, 2014).

Table 2.3: Equations for Distance Travelled During Brake Reaction Time and Braking (AASHTO, 2012)

Distance Travelled During Brake Reaction Time	
Metric	**U.S. Customary**
$d = 0.278Vt + \frac{0.039V^2}{a}$	$d = 1.47Vt + \frac{1.075V^2}{a}$
Where: t = brake reaction time, 2.5 s; V = design speed, km/h; A = deceleration rate, m/s^2	Where: t = brake reaction time, 2.5 s; V = design speed, mph; A = deceleration rate, ft/s^2
Distance Travelled During Braking	
Metric	**U.S. Customary**
$d = \frac{0.039V^2}{a}$	$d = \frac{1.075V^2}{a}$
Where: t = brake reaction time, m; V = design speed, km/h; A = deceleration rate, m/s^2	Where: t = brake reaction time, ft; V = design speed, mph; A = deceleration rate, ft/s^2

2.2.2 Bicyclist Behavior

Currently, no models exist to predict or explain bicyclist behavior. This is in contrast to both motor vehicle driver models, which have generations of improvement and increased sophistication, and pedestrian models, which have been recently formulated in the last two decades (Cacciabeu, 2017). However, studies collecting empirical video data and kinematic performance measures can give some insight into general bicyclist behavior.

A naturalistic study completed in Sweden suggests that velocity distributions for bicyclists tend to take a Gaussian shape, with the 75th percentile of bicyclists riding above 12.5 miles per hour (Dozza et al, 2014). Head checks are an important indicator of intended bicyclist behavior—more frequent head checks are associated with greater caution by the bicyclist (Johnson, 2016). After a non-door zone incident, bicyclists will tend to make more head checks toward vehicle traffic than away from vehicle traffic. Therefore, the risk of dooring due to bicyclist inattention to adjacent parallel parked cars may increase after a non-door zone incident.

Bicyclist navigation can be classified into operational, tactical, and strategical levels. Operational navigation can be thought of as a bicyclist's basic riding behavior, while tactical navigation can be thought of as a bicyclist's path choices in certain situations (such as choosing to depart the bicycle lane to avoid debris). Finally, strategical navigation refers to a bicyclist's general travelling plan (such as the bicyclist's destination and route choice) (Hoogendoorn, 2002). Each of these levels is guided by a bicyclist's sensory stimulus (e.g. sight, touch, sense of balance, etc.), which drives a bicyclist's reactions and riding preferences (Heilbing, 2000). Figure 2.6 illustrates the control and information flow in the perceptual process that dictates the decisions and actions bicyclists take. The general inputs in the perceptual process illustrated in Figure 2.6 are perception and temperament type. Temperament type includes, but is not limited to, factors such as bicyclist's individual level of aggression and preferred riding velocity.

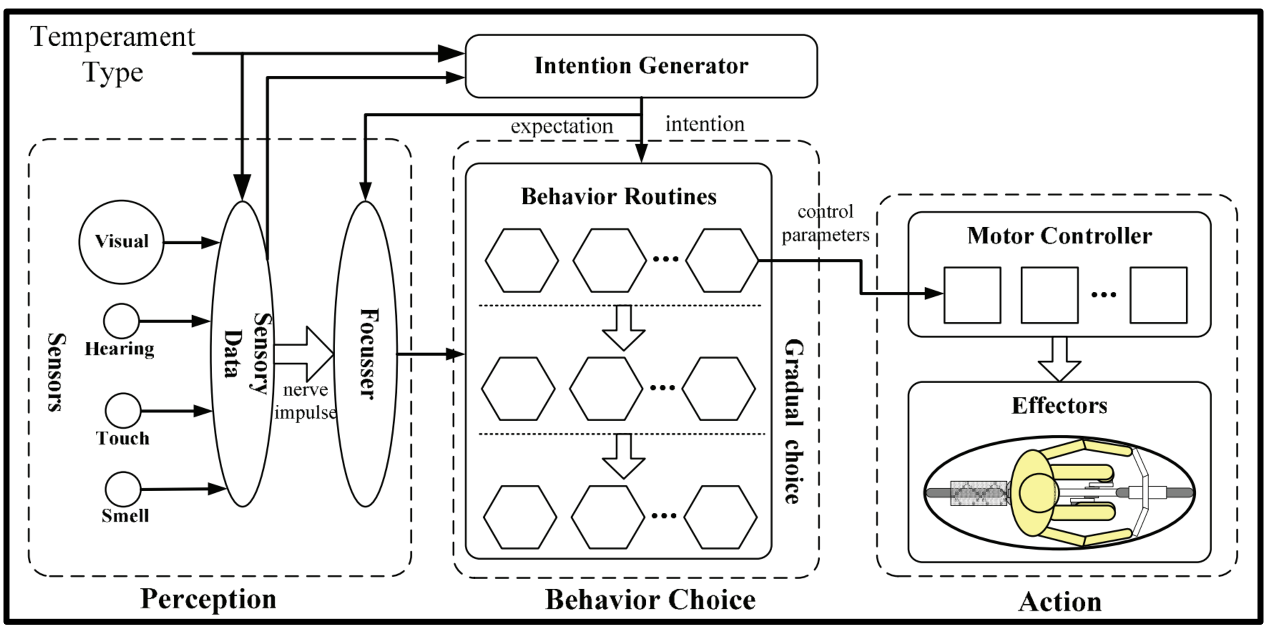


Figure 2.6: Control and Information Flow in Perceptual Process for a Bicyclist (Liang, 2012)

When compared to a driver inside a motor vehicle, a bicyclist has a greater exposure to its surrounding environment. Due to this exposure, a bicyclist has unique reaction and perception ranges. Bicyclists tend to be more aware of their surroundings through sounds, and are better able to detect smaller details in the environment than drivers in motor vehicles. Generally speaking, bicycles do not have mirrors to give a rear view of their environment, and predominately react to static or dynamic obstructions that are only in front of them (Liang, 2012). A bicyclist can also pass obstacles with a smaller clearance if the obstacle is not aligned to the center of the bicycle when first detected by the bicyclist. This means the movement of a bicycle can be considered anisotropic (Liang, 2012). When compared to motor vehicles, bicycles are more efficient at utilizing clearance, which can be attributed back to a bicyclist's unique reaction and perception ranges.

According to a study that attempted to develop a bicycle behavior model, a bicyclist's perceptive range is larger than its reactive range. Therefore, a bicyclist may perceive an object or obstruction, but choose not to react to that object or obstruction until it is within the reactive range (Liang, 2012). The study also found that a bicyclist's reaction is usually automatic, meaning reactions are determined by the bicyclist's prior experiences of which reaction is appropriate for that scenario (Liang, 2012). Therefore, hesitations in a bicyclist's reaction to an obstruction may indicate that the bicyclist has not had enough prior experience to that scenario to determine what the most appropriate reaction is.

2.2.2 Effect of Bicycle Infrastructure on Bicyclist Behavior

Bicyclists are likely to position themselves inside the door zone regardless of bicycle lane width (Fees, 2015). Up to 45% of bicyclists ride in the door zone while inside a marked bicycle lane (Fees, 2015). Bicyclists also have a bicycle zone boundary. This is the space the bicyclist prefers to have around themselves while riding on a roadway. Bicyclists tend to push their bicycle zone boundaries further to the left to avoid hazards on the right, such as open vehicle doors (Furth, 2011). However, in the presence of vehicles that are passing the bicyclist on the left, bicyclists will intentionally ride inside the door zone (Furth, 2011). When there are no vehicles passing the bicyclist on the left, bicyclists will shift their position 3.4 to 4.0 feet further away from on-street parallel parked cars when the road has marked sharrows (Furth, 2011). Still, bicyclists in marked bicycle lanes tend to ride further away from the door zone on average when compared to bicyclists riding in shared or unmarked roads (Furth, 2011). Buffered bicycle lanes also move the position bicyclists choose to ride further left, but still leaves the bicyclist within the door zone (Torbic, 2014).

Data from the Toronto Police Service shows where door zone collisions have occurred in Toronto, Canada between 2014 and 2015. This data also indicates which roadways have bicycle lanes, and which roadways are shared or unmarked. Based on Figure 2.7, it is unclear whether door zone collisions occur more frequently or less frequently on roadways with bicycle lanes.

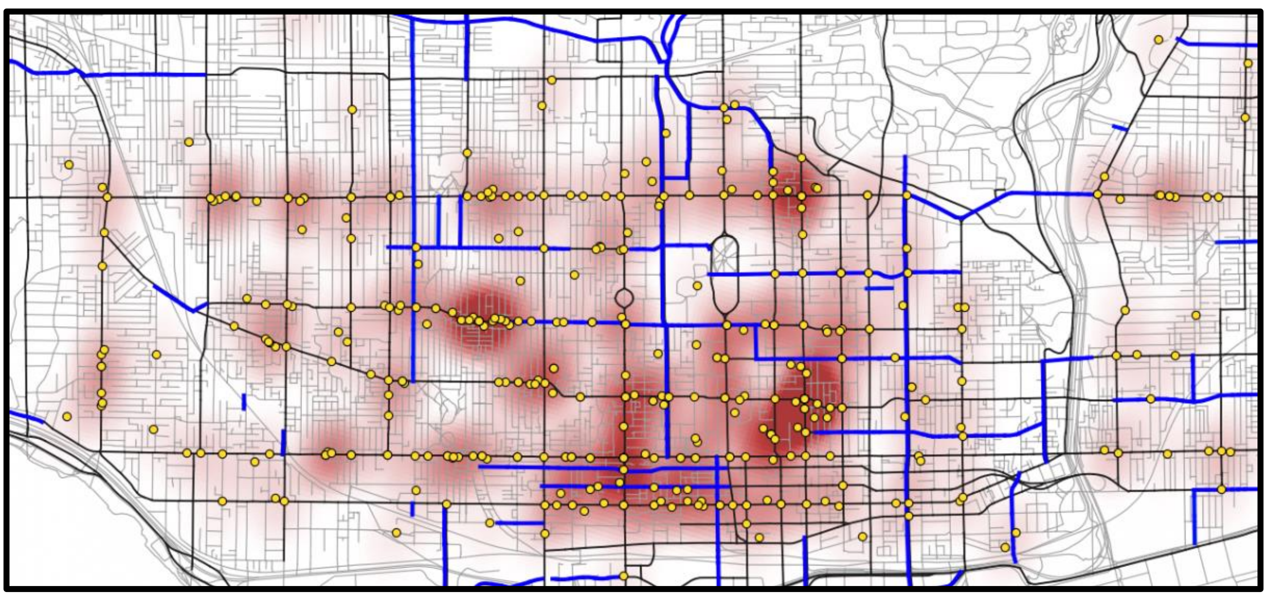


Figure 2.7: Dooring Location Heat Map in Toronto between 2014 and 2016 (yellow dot denotes collision; blue lines indicate roadway with bicycle lane) (TPS, 2016)

2.3 Door Zone Treatments

Figure 2.8 shows a visual representation of the Copenhagen Bicycling Planning Guide, which considers safe bicycle lane placement in the presence of adjacent parked cars. In this plan, the use of a physical barrier or painted buffer between the bicycle lane and adjacent on-street parallel parking is encouraged on roadways with higher design speeds. As roadway design speeds increase, it is recommended that on-street parallel parking be removed and separation between bicycle and motor vehicle infrastructure increase. Additionally, parking spaces are placed in between the bicycle lane and motor vehicle lane instead of between the bicycle lane and edge of the roadway. This eliminates the potential for a bicyclist to be thrown into the motor vehicle travel lane in a door zone collision. However, this arrangement may trap the bicyclist between the parked vehicle and the curb or edge of the roadway in a door zone collision.

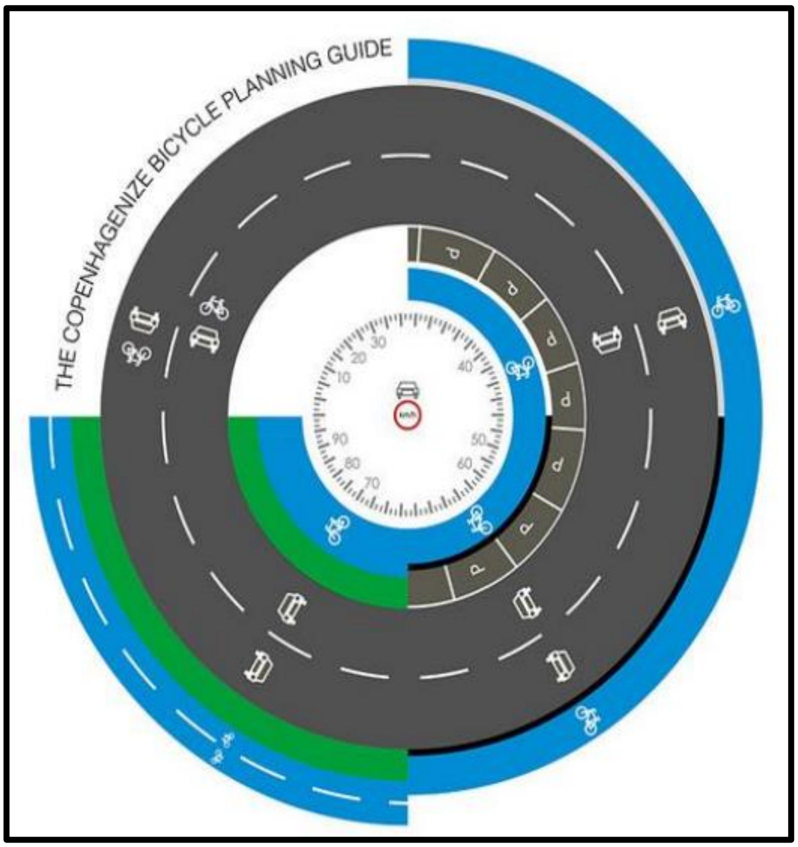


Figure 2.8: Copenhagen Bicycle Planning Guidelines for Roadway Cross-Sections based on Roadway Design Speeds (Miller, 2015)

The City of Chicago, Illinois does not stripe bicycle lanes narrower than 4 feet if adjacent to on-street parallel parking. This is done to reduce the likelihood of a bicyclist to escape from the door zone entering the motor vehicle travel lane. Chicago, Illinois also double stripes between the bicycle lane and on-street parallel parking area, which encourages motor vehicles to park closer to the curb (especially when there is a low density of on-street parallel parking) (Chicago, 2002). Disadvantages to this strategy include a lack of physical space on roadways for wider bicycle lanes and double striping, as well as additional upkeep of striping. Parking T's are suggested by the City of Los Angeles, California to reduce the risk of door zone collisions (LADCP, 2014). Parking T's are effective in moving bicycles out of the door zone, and encourages motor vehicles to park closer to the curb (Torrance, 2009). Another engineering treatment to reduce the risk of door zone collisions from a City of San Francisco, California study suggests that sharrows moved bicycles four inches further away from parked cars on average. It is important to note that while this is further away from on-street parallel parked cars, it is still within the door zone (Meng, 2012). Sharrows also reduce bicyclist confidence, and many studies show that bicycle lanes are superior to wide curb lanes and sharrows in terms of increasing bicyclist confidence and decreasing perceived risk (Torbic, 2014). Buffered bicycle lanes are more effective than widening bicycle lanes in moving the bicyclist out of the door zone than either sharrows or traditional bicycle lanes (Torbic, 2014).

Since the death of Dana Laird in 2002, a variety of public information and education campaigns have been implemented in different urban areas. For example, New York City, New York and Portland, Oregon have begun requiring taxi cabs, Uber vehicles, and Lyft vehicles to display window stickers that warn passengers to check for bicyclists before opening their door. An example sticker from Portland, Oregon is shown in Figure 2.9 (Greenfield, 2012). Another education campaign for reducing the occurrence of door zone collisions is one to teach new drivers to practice the "Dutch reach" (Cumming, 2012). The "Dutch reach" is a strategy for opening a vehicle door where the driver or passenger opening the vehicle door uses the arm furthest from the door to open it. This forces the body and eyes of the person to twist in the direction of oncoming traffic.

Figure 2.9: Example Window Sticker Used inside Taxis in Portland, OR (Cumming, 2012)

As technology in motor vehicles continues to advance, motor vehicles have the potential to be equipped with sensors and alert systems that will warn the driver or passenger of oncoming bicyclists. Motor vehicles may also be equipped with alert systems that will warn oncoming bicyclists when a driver or passenger is planning to open the vehicle door.

2.4 Bicycling Simulators

Bicycling simulators consist of cueing systems (visual, auditory, proprioceptive, motion), bicycle dynamics, computers and electronics, bicycle frame and control, measurement algorithms, data processing, and data storage (Hurwitz, 2016). The combination of these components works to stimulate the rider's sensory and perceptual systems. Bicycling simulators are an important component of transportation research, and allow researchers to study behaviors in bicyclists for scenarios which empirical data would be difficult to obtain. Table 2.4 shows an organization of the major bicycling simulator facilities involved in transportation safety research.

Table 2.4: Major Bicycling Simulator Facilities and their Specifics (Hurwitz, 2016)

Name:	Location:	Developer:	Software:	Degrees of Freedom:	Visual Angle:	Resolution:
PanoLab	Germany	Max Planck Institute for Biological Cybernetics	N/A	2	230° (H) 125° (V)	1920×1200
Hank	U.S.A.	Department of Computer Science, The University of Iowa	HCSM	2	270° (H) N/A (V)	1920×1080
FIVIS	Germany	Bonn-Rhein-Sieg University of Applied Science	FIVSim	6	180° (H) N/A (V)	1024×768
LEPSIS	France	French Institute of Science and Technology for Transport, Development and Networks	N/A	2	225° (H) 55° (V)	1280×960
Taiwan	Taiwan	Lunghwa University of Science and Technology	N/A	2	85.5° (H) 69.4° (V)	1024×768
OSU	U.S.A.	Realtime Technologies, Inc.	SimCreator	2	109° (H) 89° (V) + Side Mirror	1024×768

2.5 Summary and Motivations

Current design standards for roadway cross sections with a bicycle lane and adjacent on-street parallel parking do not provide enough physical space for bicyclists to escape the door zone without entering the motor vehicle travel lane. Door zone collisions occur most frequently in urban areas, and are usually the result of driver or bicyclist inattention. This collision type is especially dangerous due to the vulnerable position bicyclists are placed post-collision (on their head or back in the motor vehicle travel lane). Many bicyclists worry about potential collisions with vehicle doors while riding their bicycle, making the perceived risk of a door zone collision a barrier to individuals who want to ride their bicycle. Bicyclist reactive and perceptive ranges are different than that of motor vehicle drivers, with bicyclists having a larger perceptive range than reactive range.

Future research should identify factors that change a bicyclist's behavior in close proximity to the door zone (Fees, 2015). This includes gathering information on the decision making of the bicyclist when different engineering treatments are implemented (such as buffered bicycle lanes or signage), or with varying environmental factors (such as different volumes of adjacent vehicular traffic). Knowledge gaps exist in understanding the causes leading to door zone collisions (Pai, 2011). More specifically, knowledge gaps exist in the environmental factors and human factors in door zone collision. Education may be a more cost-effective solution than engineering treatments, however education is limited by the amount of knowledge currently available on the topic (Pai, 2011). Further research on door zone and door zone collision frequency with and without bicycle lanes may also be of interest (Sanders, 2013).

3 METHODS

This chapter describes the hardware and software associated with the OSU Bicycling Simulator. Additionally, a description of the types of data collected by the OSU Bicycling Simulator and the data reduction strategies used in this study will be provided. The research questions, goals, and hypothesis are stated in this chapter. The last section of this chapter discusses the target demographic, the experimental protocol for recruiting subjects, and the activities participating subjects performed during the experiment.

3.1 Experimental Equipment

Design and protocols for the experiment were developed to be optimal for addressing the research questions of interest (see section 3.2.1). This approach is grounded in accepted practice (Fisher et al, 2011) and leverages unique research capabilities at OSU. The primary facility that was utilized for this experiment was the OSU Bicycling Simulator. A description of this facility and its capabilities is provided in the following sections.

3.1.1 Bicycling Simulator

The OSU Bicycling Simulator consists of an instrumented urban bicycle placed on top of an adjustable stationary platform. A 10.5-foot by 8.3-foot screen provides the forward view with a visual angle of 109 degrees horizontally and 89 degrees vertically. The image resolution of this screen is 1024 by 768 pixels. Additionally, a small window in the top left corner of the screen provides the rider with a rear-view. Researchers build the environment subjects ride through, and track subjects from the operator workstation shown in Figure 3.1. The operator workstation is out of view from the subjects riding the bicycle in the simulator room.

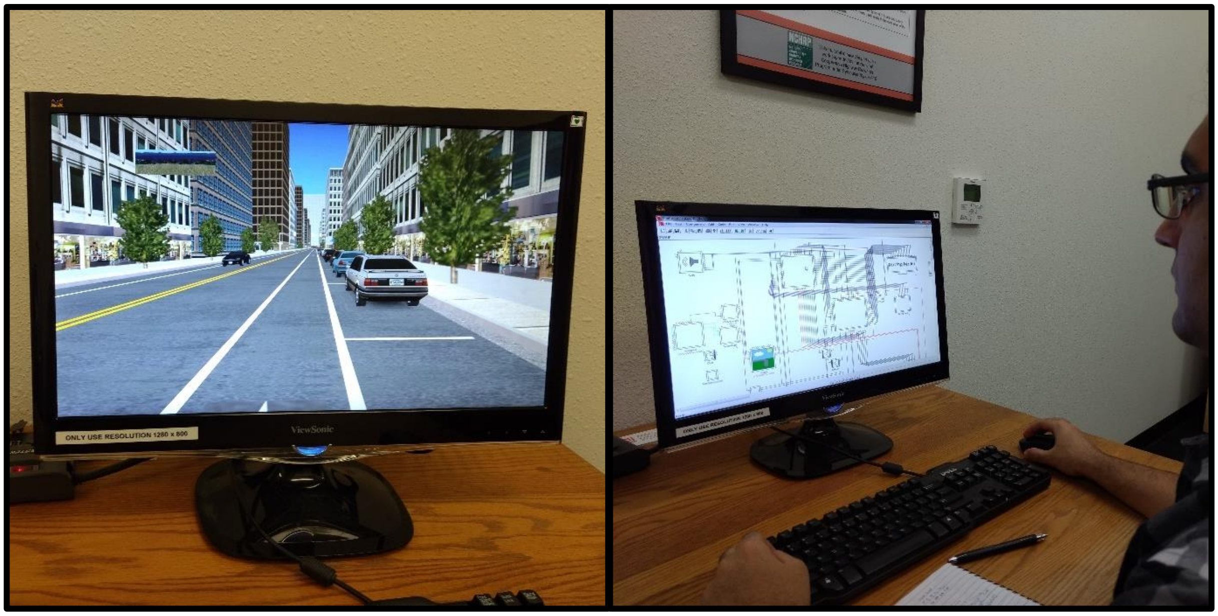


Figure 3.1: Operator Workstation for the Bicycle Simulator Running Simulation (left) and SimCreator (right)

The update rate for the projected graphics is 60 Hertz. Ambient sounds around the bicycle are modeled with a surround sound system. The computer system consists of a quad core host, which runs Realtime Technologies SimCreator Software. The graphics update rate of this system is 60 Hz. The simulator software can record values for performance measures such as velocity, position, acceleration, and deceleration with high accuracy. Figure 3.2 shows a view of the simulated environment from the participant’s view and from the outside view.

Figure 3.2: Participant's Perspective of the Simulated Environment (left) and Outside Perspective of the Simulated Environment (right)

The simulation environment is developed using the following software packages: Internet Scene Assembler (ISA), SimCreator, and Blender. The simulation animations were developed in ISA using JavaScript-based sensors on the test tracks to display dynamic objects, such as a pedestrian walking on a sidewalk.

3.1.2 Custom Objects

Pre-loaded static and dynamic objects from SimCreator were adjusted with Blender, an open source 3D modelling software as seen in Figure 3.3. Objects were adjusted to better fit the simulated environment, such as changing the texture of a static vehicle's doorway to show the inside of the vehicle. Custom objects such as the vehicle door were also created using Blender. The vehicle door has a width of 45 inches in the simulated environment, and is based on the average vehicle door width of vehicles registered in the United States (Torbic, 2014). Custom objects are static by default, and were animated in the simulated environment using JavaScript code.

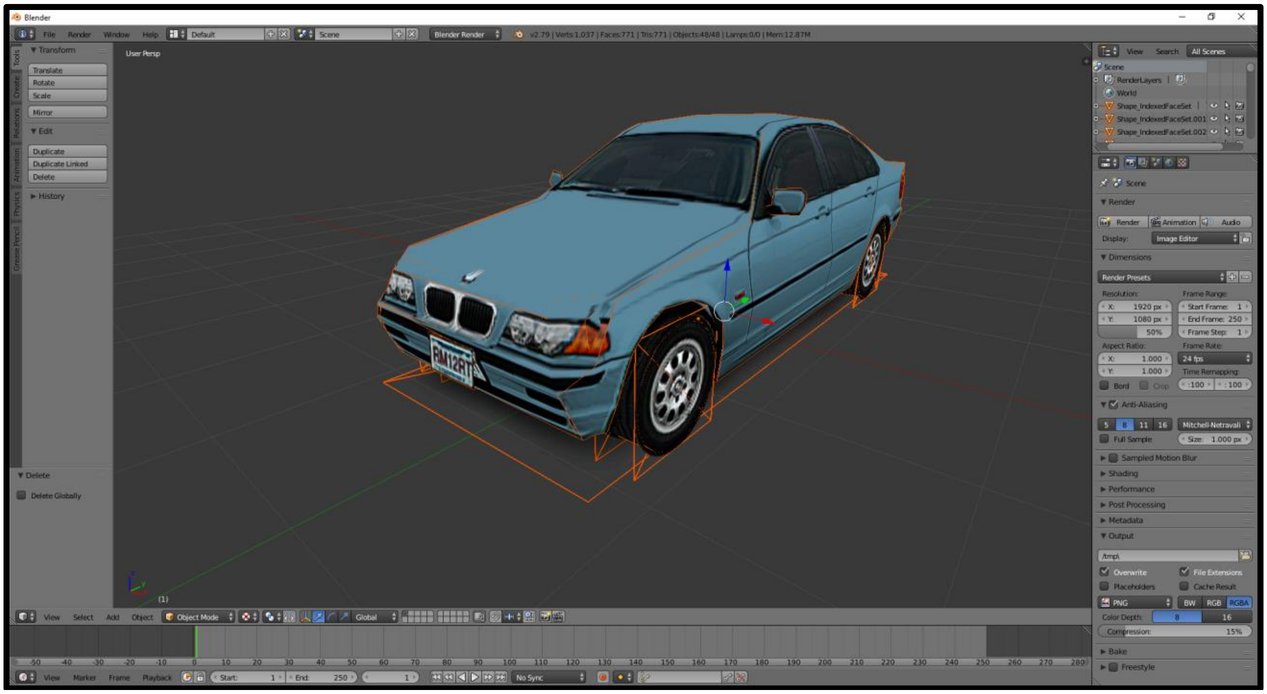


Figure 3.3: Screenshot of Blender Software Interface with Pre-Loaded Static Car Model

3.1.3 Simulator Data

The following parameters on the subject bicycle were recorded at roughly 10 Hz (10 times per second) throughout the duration of the experiment:

- Time – To map the change in velocity and acceleration with the position on the roadway;
- Instantaneous Velocity of Subject Bicycle – To identify changes in velocity approaching an open or opening vehicle door;
- Instantaneous Position of Subject Bicycle – To estimate the headways and distance upstream from an open or opening vehicle door;
- Instantaneous Acceleration and Deceleration – To identify an acceleration or deceleration approaching an open or opening vehicle door;
- SimObserver Data – The OSU Bicycling Simulator is equipped with three cameras positioned at various viewing angles to observe the actions of participants when approaching an open or

opening vehicle door. 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 of the OSU Bicycling Simulator from SimObserver

3.1.4 Eye-Tracker

In conjunction with the bicycling simulator, an eye-tracking system was used to record where participants were looking while riding in the simulator. Eye-tracking data was collected with the ASL Mobile Eye-XG platform, shown in Figure 3.5. The device allows the user to make unconstrained eye and head movements. Data from the eye-tracking system was collected at a rate of 30 Hz (30 times a second), with an accuracy of 0.5 degrees to 1.0 degree (OSU Driving and Bicycle Research Lab, 2011). The participant's gaze was calculated based on the correlation between the participant's pupil position and the reflection of three infrared lights on the eyeball. Eye movement consists of both fixations and saccades. Fixations occur when the gaze is directed toward a location and remains still for some period (Green 2007; Fisher et al, 2011). Saccades occur when the eye moves between fixations.

The ASL Mobile Eye-XG system records a fixation when the participant's eyes pause in a certain position for more than 100 milliseconds. Quick movements to another position (saccades) are not recorded directly, but are calculated based on the dwell time between fixations. Total dwell times are recorded by the equipment as the sum of the time of fixations and saccades consecutively recorded within an area of interest (AOI).

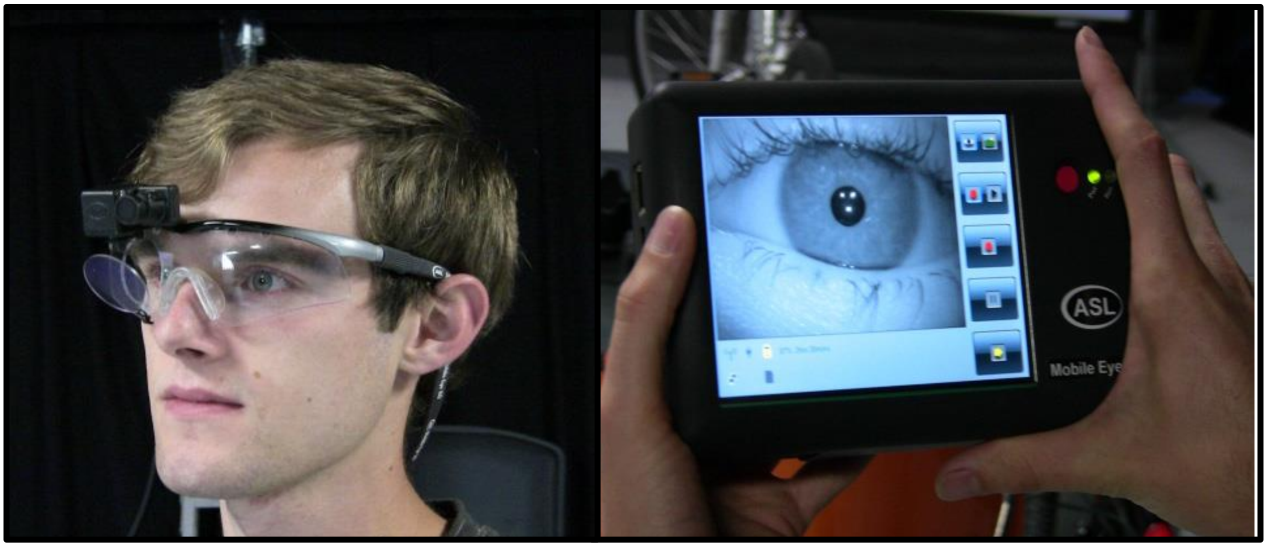


Figure 3.5: OSU Researcher Demonstrating the Mobile Eye XG Glasses (left) and Mobile Recording Unit (right)

3.1.5 Simulator Sickness

Simulator sickness is a phenomenon where a person exhibits symptoms similar to motion sickness that is 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 is the cue conflict theory. The cue conflict theory suggests that simulator sickness 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 bicycle simulation that would suggest motion sickness issues in bicycling simulators. However, precautions were taken to ensure comfort for all participants. Data from participants who experienced simulator sickness during the study were not included in the project’s results.

3.2 Experimental Design

To address the research questions related to the behavior of bicyclists in the door zone, an experiment was designed using the OSU Bicycling Simulator and the eye-tracker equipment. The experiment also tests the hypothesis stated in section 3.3.2.

3.2.1 Research Questions and Goals

The specific research questions associated with the assessment of bicyclists' performance and crash avoidance are as follows:

- *Research Question 1 (RQ1)*: Does the time to the open door and remaining amount of space in a bicycle lane with an open vehicle door have any effect on the bicyclists' lateral position?
- *Research Question 2 (RQ2)*: Does the time to the open door and remaining amount of space in a bicycle lane with an open vehicle door have any effect on the bicyclists' velocity?
- *Research Question 3 (RQ3)*: Does the time to the open door and remaining amount of space in a bicycle lane with an open vehicle door have any effect on the bicyclists' acceleration?

The specific goals associated with this research study are as follows:

- Provide further evidence for or against a correlation between bicyclist experience with door zone or door zone related collisions and their perceived risk of door zone or door zone related collisions through survey data.
- Collect time, lateral position, velocity, and eye-tracking data from participants as they are exposed to all six door zone scenarios (scenario descriptions can be found in section 3.2.3).
- Identify thresholds in terms of time to the open door and amount of space in a bicycle lane with an open vehicle door in which most bicyclists choose to depart the bicycle lane to maneuver around the vehicle door.

- Identify thresholds in terms of time to the open door and amount of space in a bicycle lane with an open vehicle door in which most bicyclists choose to accelerate past the vehicle door, or slow down before the vehicle door.
- Apply identified thresholds discussed in the previous two goals to potential engineering treatments for door zone or door zone related collisions.

3.2.2 Hypothesis

In terms of velocity, participants will be more likely to decelerate or come to a complete stop when encountering an open vehicle door in the simulated environment if given a shorter time to open door and smaller effective bicycle lane width. Participants will be more likely to maintain their velocity if given a longer time to open door and larger effective bicycle lane width. In terms of lateral position, participants will be neither more likely or less likely to depart the bicycle lane when given a shorter time to open door. Participants will be more likely to depart the bicycle lane when given a smaller effective bicycle lane width, and less likely to depart the bicycle lane when given a larger effective bicycle lane width.

3.2.3 Factorial Design

Two within-subject variables are included in the experiment: effective bicycle lane width with an open vehicle door, and time to the open door (Table 3.1). Figure 3.6 shows the three effective bicycle lane widths participants encounter in the simulation.

Table 3.1: Experimental Factors and Levels

Variable Name	Level	Levels Description
Effective Bicycle Lane	0	3 feet
	1	2 feet
	2	1 foot
Time to the Open Door	0	Short (0 to 5 seconds)
	1	Long (greater than 5 seconds)

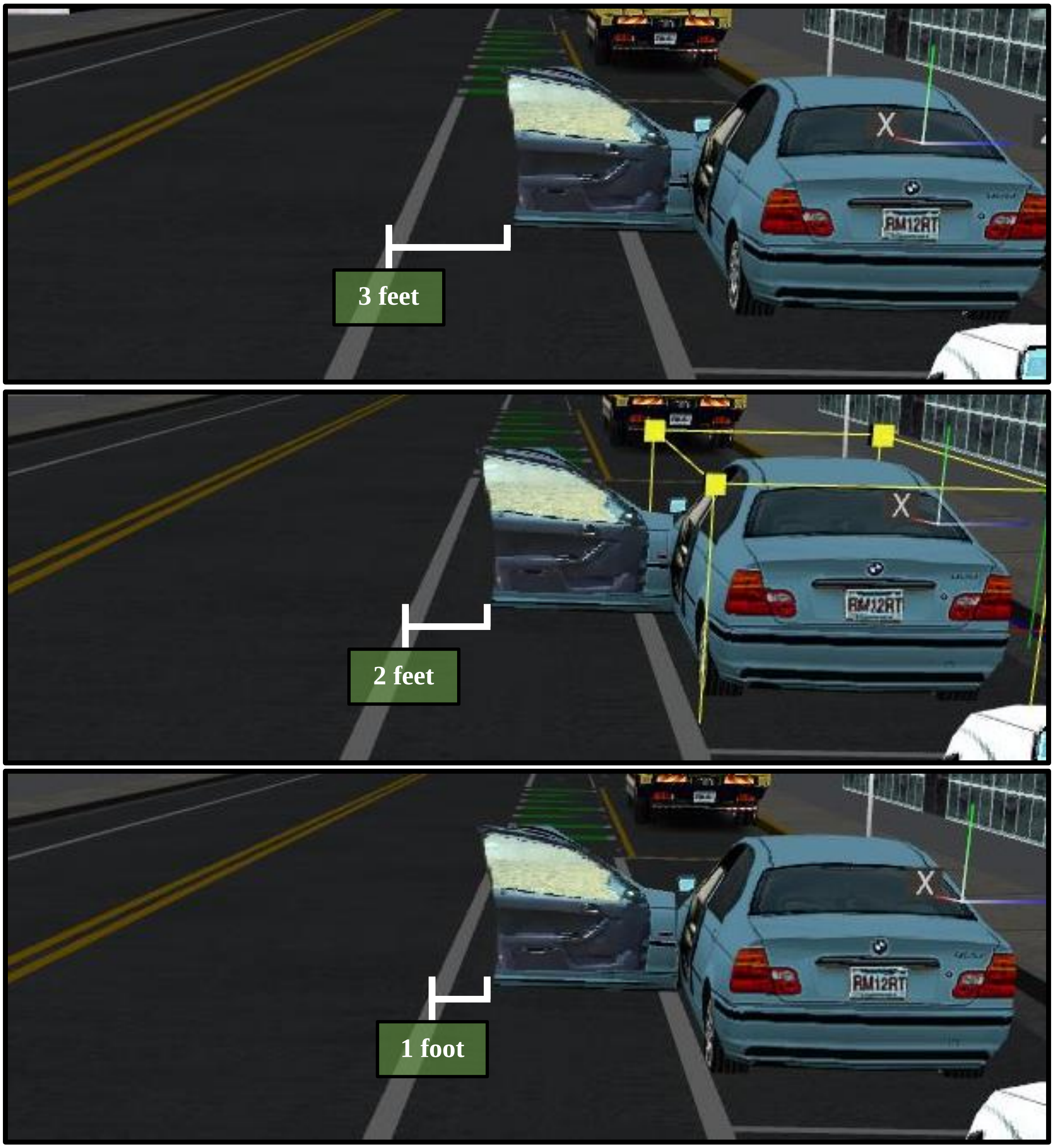


Figure 3.6: From Top to Bottom: 1-foot Effective Bicycle Lane Width (level 0), 2-Foot Effective Bicycle Lane Width (level 1), 3-Foot Effective Bicycle Lane Width (level 2)

Values for the three levels of effective bicycle lane width in the simulated environment (3 feet, 2 feet, and 1 foot) are based on specifications from AASHTO for roadway cross sections with on-street parallel parking adjacent to bicycle lanes (Torbic, 2014). Two levels of time to the open door were used in the simulation. Because of variability in bicyclist velocity, a range of 0 to 5 seconds was used as a short time to the open door. The long time to the open door used a range of greater than 5 seconds. Time to the open door is defined as the time from when the vehicle door is first detectable by the bicyclist (time t_1), to when the bicyclist passes the vehicle door. This calculation assumes that the bicyclist is travelling at a constant velocity equal to its approach velocity, or its velocity at time t_1.

These within-subject variables and levels resulted in a study with a 3 x 2 factorial design. The roadway cross-section included two 12-foot motor vehicle travel lanes with 6-foot bicycle lanes in each direction. An 8-foot parallel parking lane adjacent to a bicycle lane was also included throughout the simulated environment. Nearly all parallel parking spaces were occupied by static vehicles in the simulation.

Three primary dependent variables were observed based on the research questions and within-subject variables selected for this experiment. Visual attention was recorded from the eye-tracking equipment. Velocity and lateral position of the participant bicyclist were observed from the simulator data to determine how participants decelerated or shifted position while approaching an open vehicle door. These changes can demonstrate potentially unsafe driver behavior, such as sharp braking or crossing a bicycle lane line into conflicting motor vehicle traffic. Response times could also be calculated by cross-referencing eye-tracking data, velocity data, and lateral position data. Data was reduced to the area of interest, which was defined as 22 meters before and 12 meters after the open vehicle door. This area encompasses when the vehicle door was first visible to the bicyclist and the bicyclist's complete maneuvers around the open vehicle door for all participants in this study.

Controlled variables were used in the experiment to limit the number of outside factors that could influence participant decisions and behavior in the simulated environment. The same bicycle, a 21-speed stepover hybrid with cruiser handlebars, was used for each participant. During the calibration ride, participants were asked to find a gear of the 21-speeds which they were most comfortable riding with. Following the calibration ride, participants were not allowed to change gears again while riding through the experimental ride. Additionally, participants were asked to wear clothing that would not be restrictive to normal bicycling movements. During the experimental ride, participants were given rest and water when needed between grids (a description of the grids in the experimental ride can be found in the next section). This reduced the possibility of fatigue becoming a factor in the experiment.

3.2.4 Bicycling Scenarios

Six scenarios were presented to participants across three grids (Table 3.2).

Table 3.2 Door Zone Scenarios by Grid

Time to the Open Door (seconds)	Effective Bike Lane (feet)
Grid 1	
0-5	3
+5	2
Grid 2	
0-5	1
+5	3
Grid 3	
0-5	2
+5	1

Figure 3.7 shows an example grid layout. Participants began at the start line and rode through two door zone conflicts. Vehicles with opening doors were placed randomly between

clusters of parallel parked cars along the roadway. The bicyclist was prompted to stop pedaling at the finish line, at which time the researcher terminated the simulation. The grids simulated an urban environment with dynamic motor vehicle traffic and pedestrian traffic, as well as signalized intersections. Open vehicle doors were placed away from these dynamic components to ensure other factors were not influencing the participant's behavior in close proximity to the door zone.

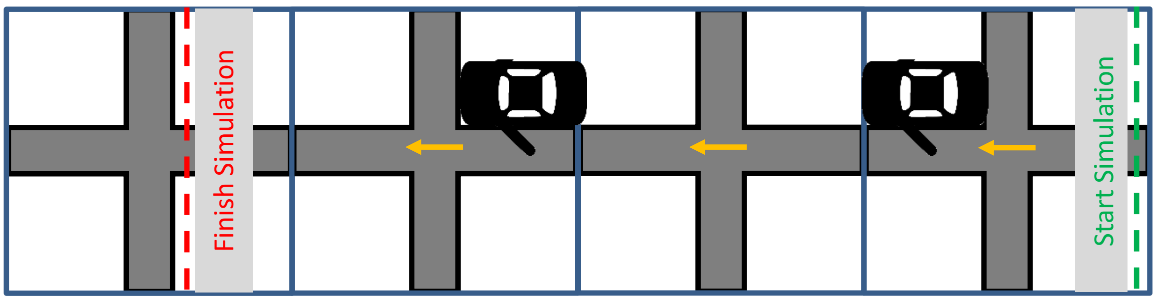


Figure 3.7 Example Grid Layout with Two Door Zone Conflicts

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

The target demographic for this study was people in the OSU community who used their bicycle to commute. All participants were required to have recent experience (within the past year) of riding a bicycle, as well as be physically and mentally capable of appropriately controlling a bicycle. All participants needed to be competent to provide informed consent. Participants were excluded if they used corrective glasses while bicycling, however contact lenses were acceptable. Participants were recruited through a combination of email advertisements, printed flyer advertisements, and community newsletter announcements.

The simulator study had a maximum enrollment of 100 participants (50 males and 50 females). Researchers did not screen interested participants based on gender until the quota for either males or females had been reached, at which point only the gender with the unmet quota was allowed to participate. 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 7979 was presented and explained. It provided the participant with the opportunity to gain an overall idea of the entire experiment and ask any questions regarding the study. 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. Participation was entirely voluntary.

3.3.3 Prescreening Survey

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

- Vision – Participants' vision is crucial for the experiment. Participants were asked if they use corrective glasses or contact lenses while bicycling. It is insured during the calibration ride that the participants could clearly see the simulated environment and read the visual instructions displayed on the screen to stop bicycling at the end of the simulation.

- Simulator sickness – Participants with previous bicycling simulation experience were asked about any simulator sickness they experienced. If they had previously experience simulator sickness, they were encouraged not to participate in the experiment.
- Motion sickness – Participants were surveyed about any kind of motion sickness they have experienced in the past. If an individual had a strong tendency towards any kind of motion sickness, they were encouraged not to participate in the experiment.

3.3.4 Calibration Ride

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

The average velocity of the participant was recorded during the calibration ride. The simulation was calibrated to the participant's average riding velocity to ensure that the time to the open door in the experimental rides would fall under the specified ranges (0-5 seconds for short time to the open door, 5 seconds or greater for long time to the open door). Participants were asked to choose a gear (of 21 potential speeds) which they were most comfortable riding with, and were not allowed to change gears during the experimental ride. This also ensured that the time to the open door in the experimental rides would fall under the specified ranges.

3.3.5 Eye-Tracking Calibration

After the calibration ride was completed, researchers equipped participants with a head-mounted eye-tracker. Participants were directed to look at different locations on a calibration image projected on the forward screen of the bicycling simulator (Figure 3.8). If the eye-tracking equipment was unable to perform the calibration, which depended on eye position and other physical attributes of the participant, then the experiment was not continued.

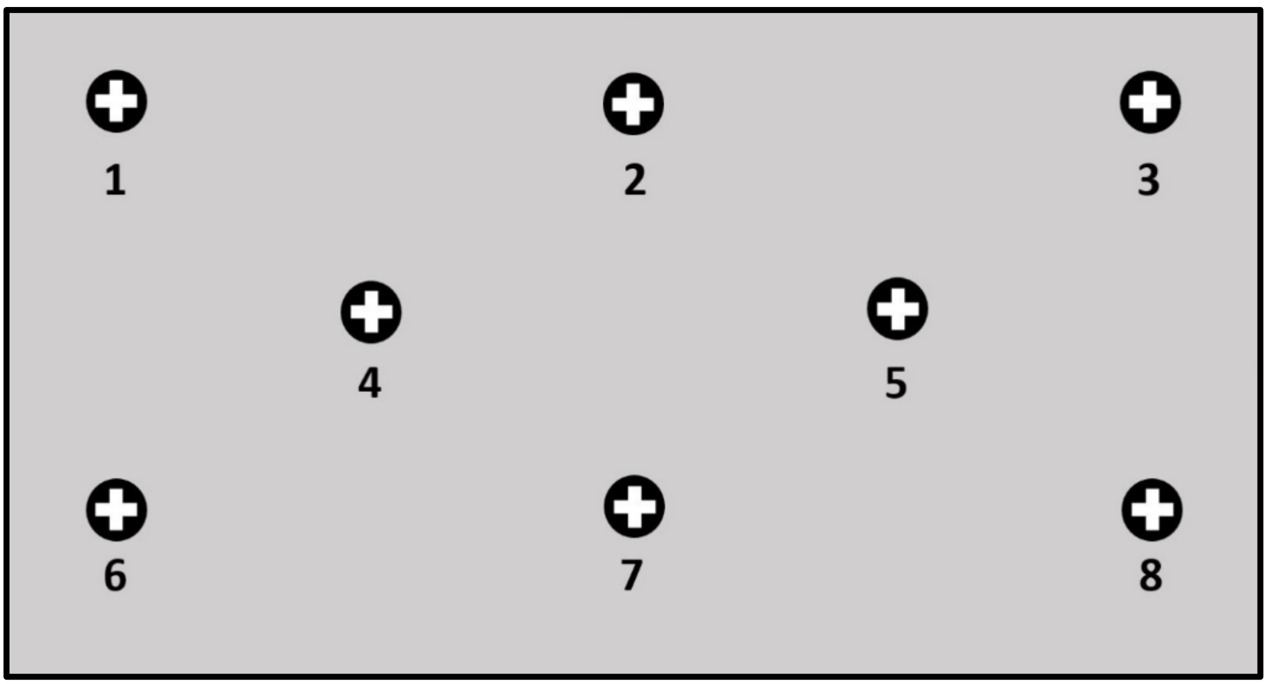


Figure 3.8: Eye-Tracking Calibration Image

3.3.6 Experimental Ride

Participants were given brief instructions about the test environment and the tasks they would be required to perform. Instructions included the request to stay in the same gear through all three grids, not to turn off the main road in the simulated environment, and to stop pedaling when instructed to do so by on-screen text at the end of the simulation. Participants were also made aware of the number of grids they would be riding through, but were not told specific information on what door zone scenarios or how many door zone scenarios each grid contained. The three virtual bicycling grids that made up the experimental rides were designed to take the participant a combined 15 to 20 minutes to complete.

3.3.7 Simulator Data

Simulator data was collected from the bicycling simulator and SimObserver platform during the experiment. A complete data file was generated for each participant for each of the three experimental rides. Files, including collected video data and all output of bicycle performance measures (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 3.9 shows the SimObserver video output in conjunction with numerical data (right side) and graphical representations of data in columns (bottom) opened by Data Distillery. Raw data (in comma delineated format) was also imported into Microsoft Excel for further data reduction and analysis. More information on the data reduction and analysis done for this project can be found in Section 4.2.

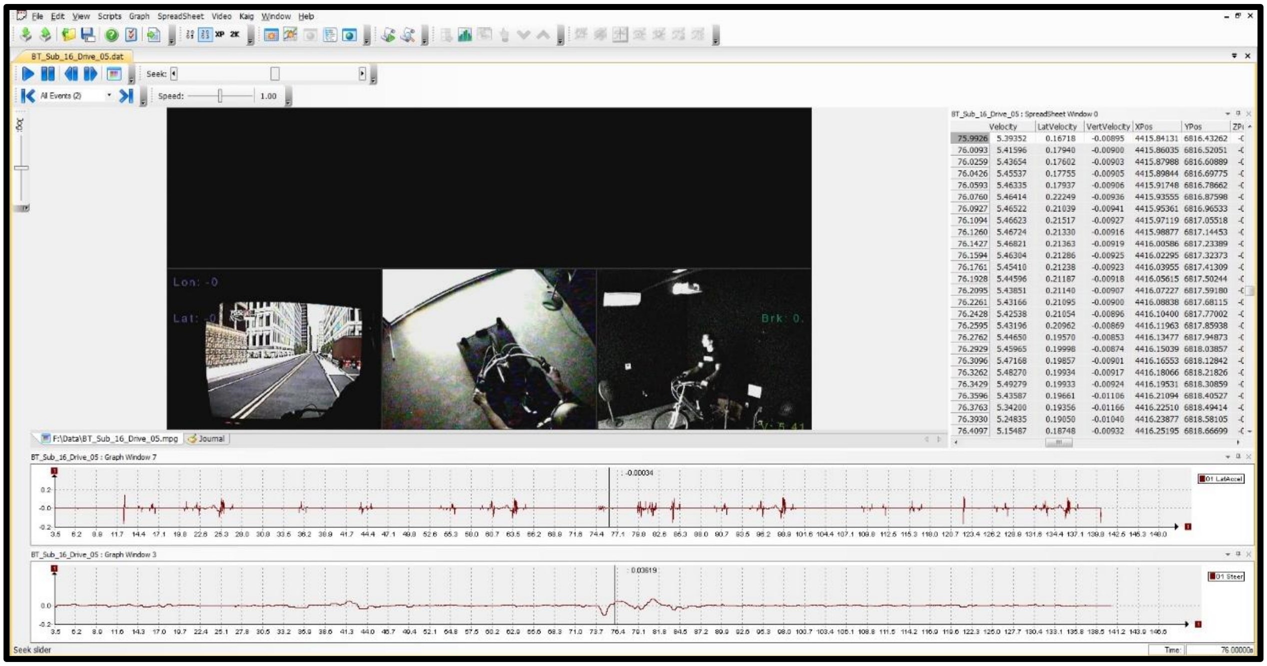


Figure 3.9 Screenshot of *Data Distillery* Software Interface with SimObserver Data

3.3.8 Post-Ride Survey

As the final step of the experiment, riders were asked to respond to questions in a post-ride digital survey. The survey included questions about the participant's previous experiences with door zone collisions. Questions about the level of concern with door zone collisions that participants feel while riding their bicycle were also asked in the post-ride survey.

3.3.9 Summary

The entire experiment, including the consent process, eye-tracker calibration, simulation, and post-drive survey, lasted about 30 minutes. Figure 3.10 provides a flow chart for the experimental protocol used for this study.

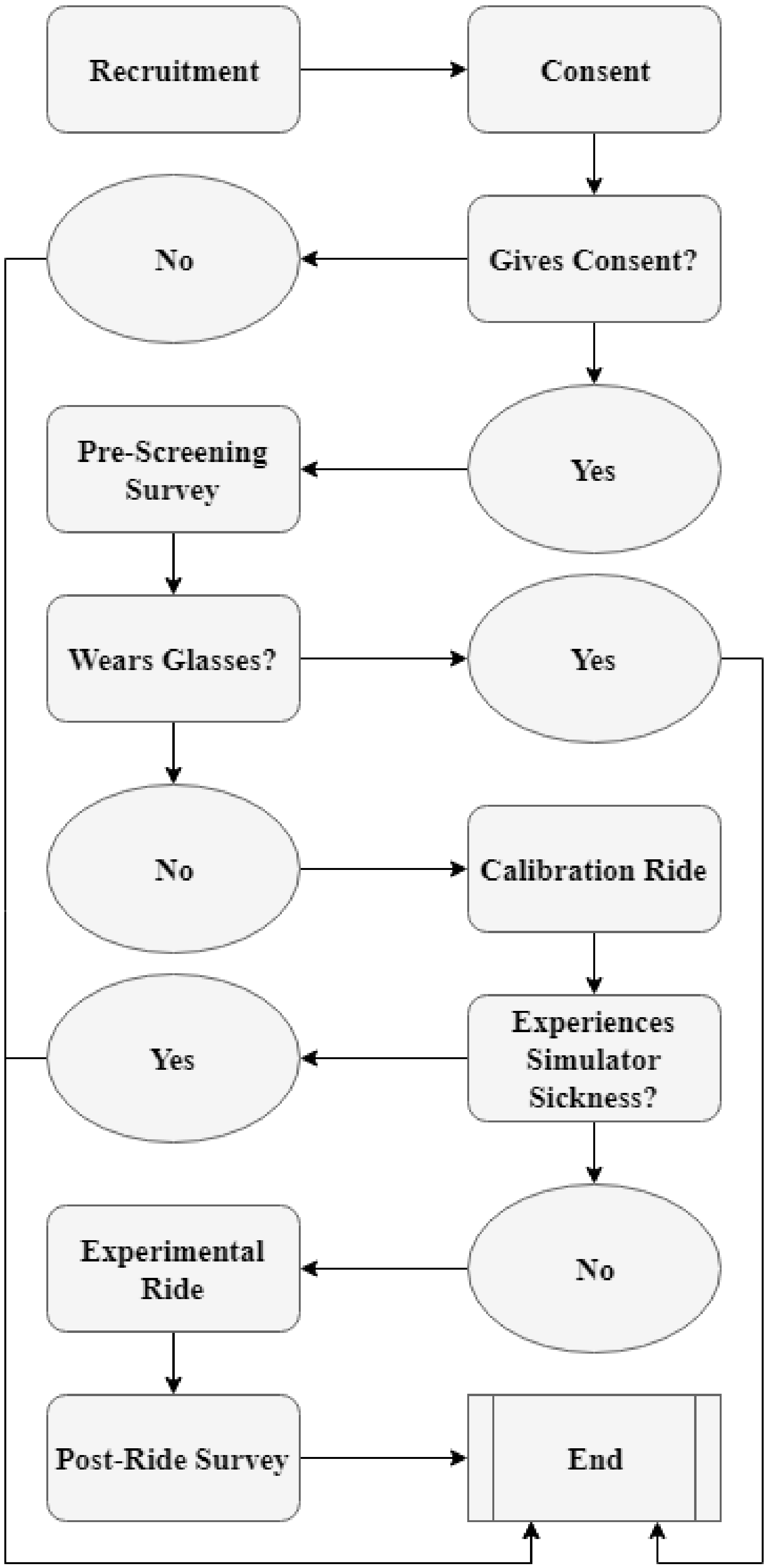


Figure 3.10 Flow Chart of Experimental Protocol Used

4 RESULTS AND ANALYSIS

This chapter presents the results of the simulator experiment and post-ride survey. The first section describes the participant demographics and post-ride survey results. The next section investigates bicyclist's performance in the door zone in terms of both velocity and lateral position. The final section of this chapter highlights selected events in which individual participants experienced a near miss situation.

4.1 Participant Demographics and Post-Ride Survey Results

4.1.1 Participant Demographics

Participants for this study were recruited from the OSU community and around the Corvallis-Albany, Oregon area. The simulator experiment was successfully completed by 21 participants. Table 4.1 shows demographic information of all 21 participants. Most participants were 18-24 years old, and had completed some college at the time of their participation. This is representative of the demographics of the OSU community. No participants between the ages of 55 and 64 participated in the experiment. Therefore, conclusions from the results of this experiment should not be generalized to all age groups. Table 4.2 gives information on participant bicycling experience. Over two-thirds of participants ride their bicycle for commuting purposes, and over two-thirds of participants ride their bicycle primarily in bicycle lanes. The majority of participants have had prior experience riding their bicycle adjacent to on-street parallel parking.

Table 4.1 Participant Demographics

Demographics	**Categories**	**Number of Participants**	**Percentage of Participants**
Age	18 – 24 years	17	81 %
	25 – 34 years	1	4.8 %
	35 – 44 years	1	4.8 %
	45 – 54 years	1	4.8 %
	55 – 59 years	0	0.0 %
	60 – 64 years	0	0.0 %
	65 – 74 years	1	4.8 %
Gender	Male	11	52 %
	Female	9	43 %
	Prefer Not to Answer	1	4.8 %
Education	High School Diploma or GED	2	9.5 %
	Some College	15	71 %
	Trade/Vocational school	0	0.0 %
	Associate Degree	1	4.8 %
	Four-year Degree	2	9.5 %
	Master’s Degree	1	4.8 %
	PhD Degree	0	0.0 %

Table 4.2 Participant Bicycling Experience

Demographics	**Categories**	**Number of Participants**	**Percentage of Participants**
Bicycling Frequency	1-2 Times Per Day	10	48 %
	1-2 Times Per Week	4	19 %
	1-2 Times Per Month	4	19 %
	Less Than 1-2 Times Per Month	3	14 %
Average Ride Duration	Less Than 10 Minutes	6	29 %
	10-20 Minutes	7	33 %
	20-30 Minutes	3	14 %
	More Than 30 Minutes	5	24 %
Reason for Riding	Recreation	4	19 %
	Commuting	16	76 %
	Sport	1	4.8 %
Bicycle Facility Most Frequently Used	Bicycle Lane	16	76 %
	Multi-Modal or Bicycle Path	1	4.8 %
	Shared Road	2	9.5 %
	Sidewalk	1	4.8 %
	Other	1	4.8 %
Experience Riding Adjacent to On-Street Parallel Parking	Yes	18	86 %
	No	3	14 %

4.1.2 Post-Ride Survey Results

In the post-ride survey, participants were asked to indicate the frequency of which they felt concern about being hit by a vehicle door while riding their bicycle. 43% of participants indicated that they were concerned “Most of the Time” or “Always”. Only 5% of participants indicated that they have never felt concern about being hit by a vehicle door while riding their bicycle. The full distribution of responses is shown in Figure 4.1.

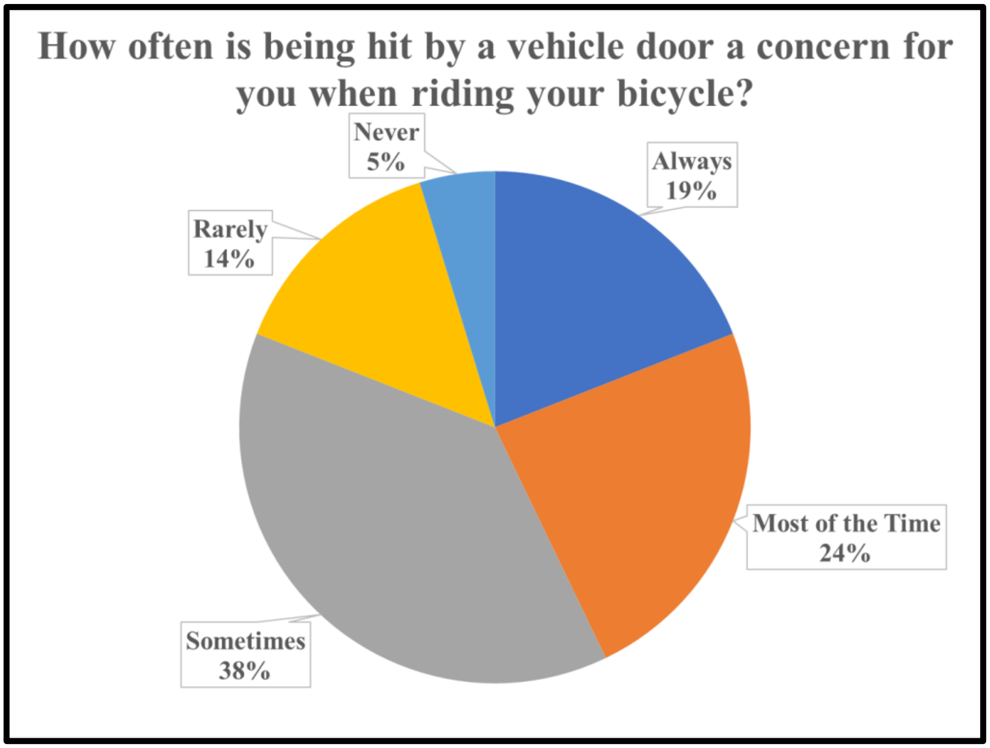


Figure 4.1 Participant Responses on Level of Concern for Collisions with Vehicle Doors

To better understand participant levels of experience with this specific conflict, participants were asked to approximate the number of times they have been in a collision or near miss situation with a vehicle door while riding a bicycle. Under 5% of participants had experienced a collision, however over 50% of participants had experienced a near miss situation. One outlier response had experienced 20 near miss situations. It is important to note that the survey did not explicitly define a "near-miss collision." Perceptions of what qualifies as a "near-miss collision" may differ between participants. The full distribution of responses is shown in Figure 4.2. Both Figure 4.1 and Figure 4.2 reveal that at least half of the participants had a predisposed awareness of door zone collisions.

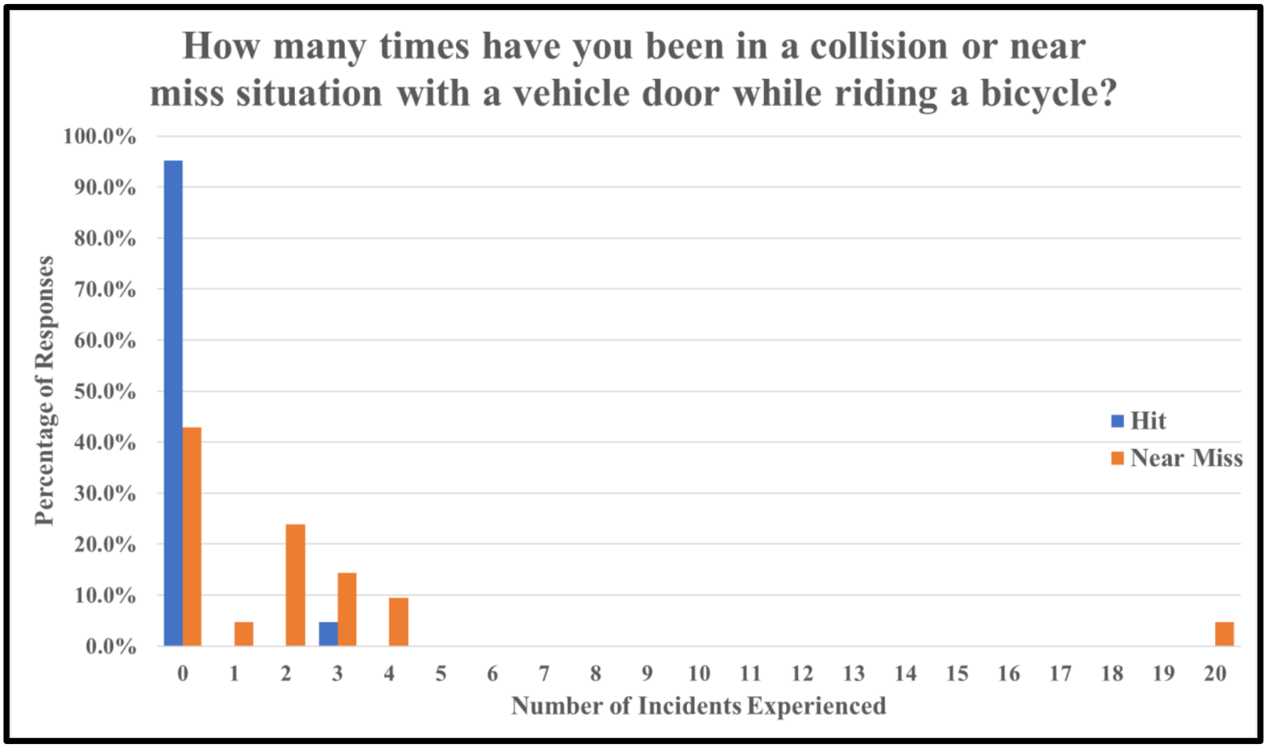


Figure 4.2 Participant Experience with Collisions or Near-Miss Situations with Vehicle Doors

4.2 Bicyclist Performance

Of the data collected by the bicycling simulator, the data of particular interest in this study was that of velocity and lateral position. These two performance measures were collected throughout the entire simulation. The data was reduced to the area of 22 meters before the open vehicle door and 12 meters after the open vehicle doors for all six door zone scenarios. These distances were chosen to capture the general range in which the door is visible to the bicyclist. This range also captures each participant's complete maneuvers around the open vehicle door for all six door zone scenarios.

A two-way repeated measures analysis of variance (ANOVA) test was performed to analyze the statistical significance of the data collected. Bicyclist velocity and bicyclist lateral position were analyzed as separate dependent variables, with time to the open door (TTD) and effective bicycle lane width (referred to simply as "width" in the figures and tables in this chapter) as within-subject variables. A significance level of 0.05 was used.

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 within-subject variables are significantly different. Mauchly's test was nonsignificant for the data from this experiment, confirming that the condition of sphericity has been met. Statistical analysis was completed using IBM SPSS Statistical Software.

4.2.1 Velocity

Mean, median, and standard deviation (SD) values for velocity at each level of each within-subject variables are reported in Table 4.3. The mean and median values for each respective scenario are relatively close, suggesting balance in the data. Bicyclists had the highest mean velocity when given a long time to the open door and 1 foot of effective bicycle lane width with the vehicle door fully opened. Adversely, bicyclists had the lowest mean velocity when given a short time to the open door and 3 feet of effective bicycle lane width.

Table 4.3 Means and Standard Deviations of Velocity (m/s)

		1-Foot Width	**2-Foot Width**	**3-Foot Width**
Short TTD (0-5 seconds)	Mean	4.9	5.6	3.4 (min)
	Median	4.3	5.5	4.1 (min)
	SD	2.1	1.8	1.7
Long TTD (5+ seconds)	Mean	6.0 (max)	5.4	5.8
	Median	5.7 (max)	5.2	5.3
	SD	1.9	1.8	2.1

Two-way repeated measures ANOVA tests were used to determine effects of factors on mean bicyclist velocities in each of the six door zone scenarios. A confidence interval of 95 percent was used. As shown in Table 4.4, the one-way interaction of time to the open door and the two-way interaction of time to the open door × width had significant effects on bicyclist velocity. No significant effect was observed for the one-way interaction of width on bicyclist velocity. In terms of within-subject variables, time to the open door accounted for the majority (45%) of variance. Figure 4.3 illustrates the two-way interaction on bicyclist velocity according to the two-way repeated measures ANOVA analysis.

Table 4.4 Two-Way Repeated Measures ANOVA Results on Velocity (m/s)

Source	F (degrees of freedom)	Significance	Partial Eta Squared
TTD	16 (1)	0.01	0.45
Width	1.7 (2)	0.19	0.08
TTD × Width	7.7 (2)	0.01	0.29

[a]*F denotes F statistic*
[b]*Statistically significant at 95% confidence interval*

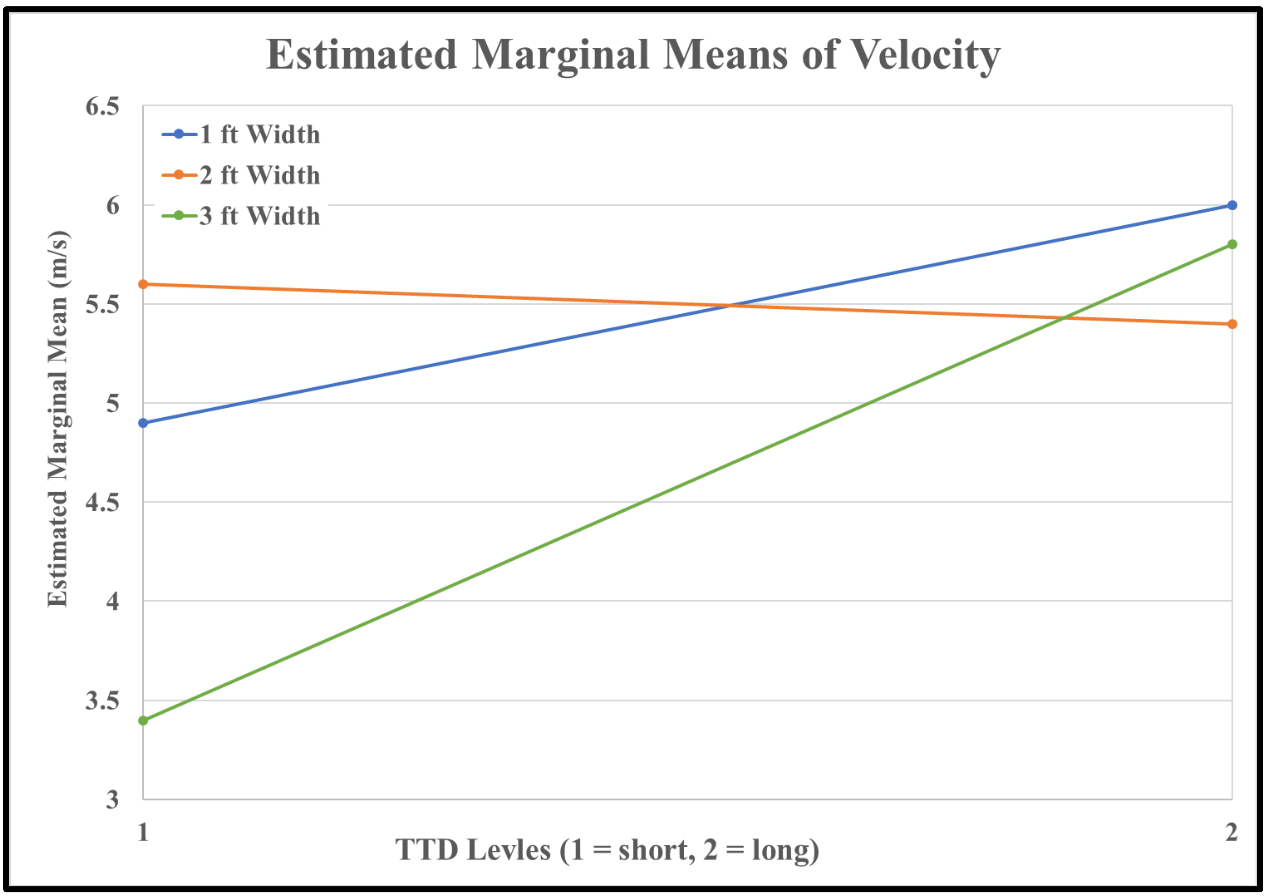


Figure 4.3 Graphical Representation of Two-Way Interactions on Velocity (m/s)

Figures 4.4 through 4.9 plot velocity distributions for individual participants, and for the entire dataset aggregated at every 2 meters. Velocity (meters per second) is plotted against distance along the bicycle lane (meters). The open vehicle door is located at 0 meters in the following figures, and is denoted by a red dashed line in the velocity distribution plots for individual participants. Each line in the velocity distribution plots for individual participants represents one participant. The aggregated plots (the plots at the bottom of each figure) display the mean (horizontal line inside box) and standard deviation (vertical bars extending above and below box) values at every 2 meters, which is overlaid on individual participant data (dots).

As illustrated by the figures, there are two common velocity patterns as participants approach 0 meters: maintaining their velocity through 0 meters or reducing their velocity before 0 meters. Some participants also chose to accelerate through 0 meters, usually in an attempt to pass the vehicle door before it has fully opened. The spread of velocities is more pronounced in scenarios with a short time to the open door versus a long time to the open door. Small dips in individual velocities before 0 meters may indicate hesitations by the bicyclist. This suggests a point where the bicyclist is unsure of whether the safest decision is to decelerate or continue past the open vehicle door.

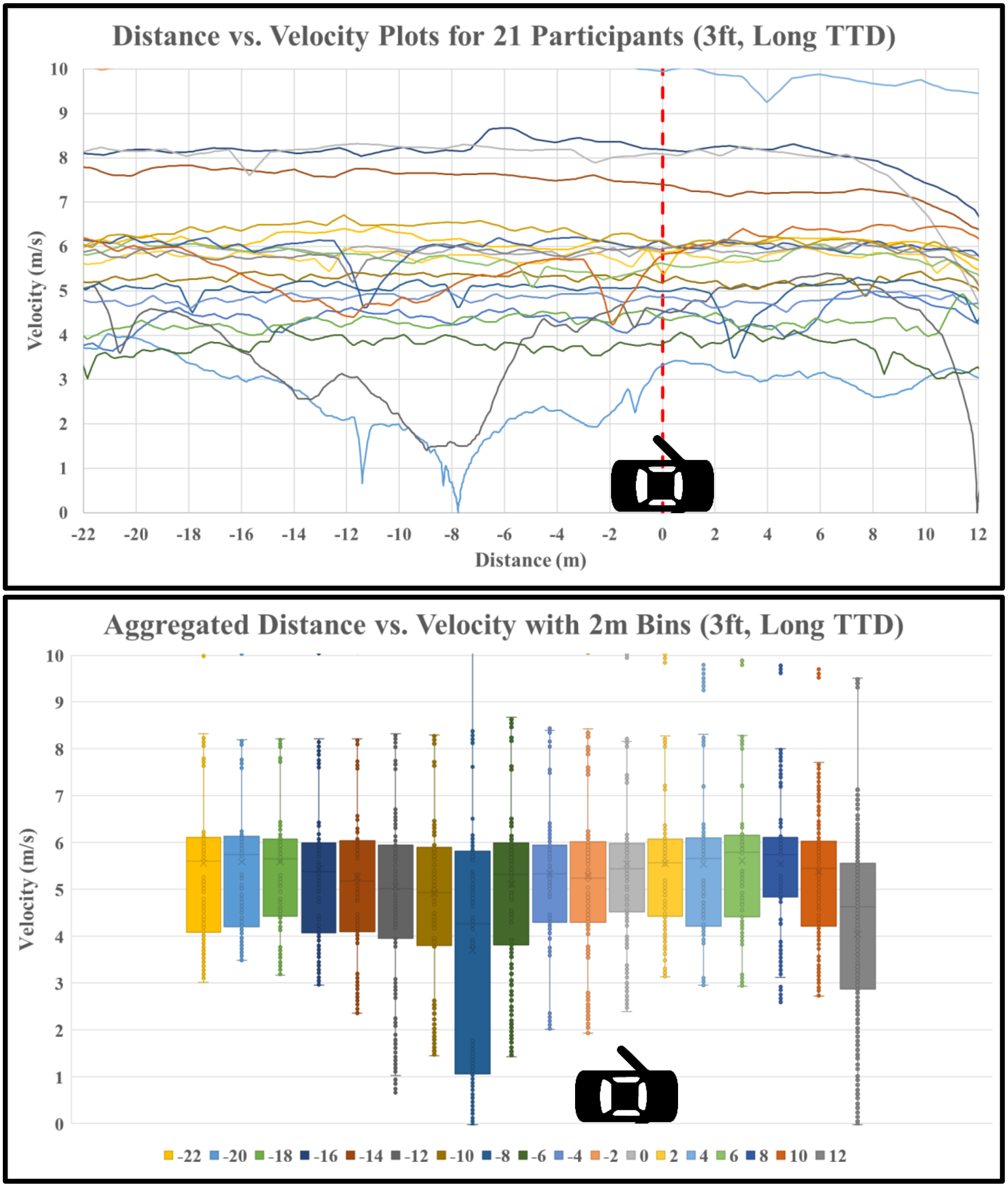


Figure 4.4 Bicyclist Velocity at Open Vehicle Door (3-foot effective bicycle lane width, long time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box*

[b]*Standard deviation denoted by bars extending above and below box*

[c]*Individual participant data denoted by dots*

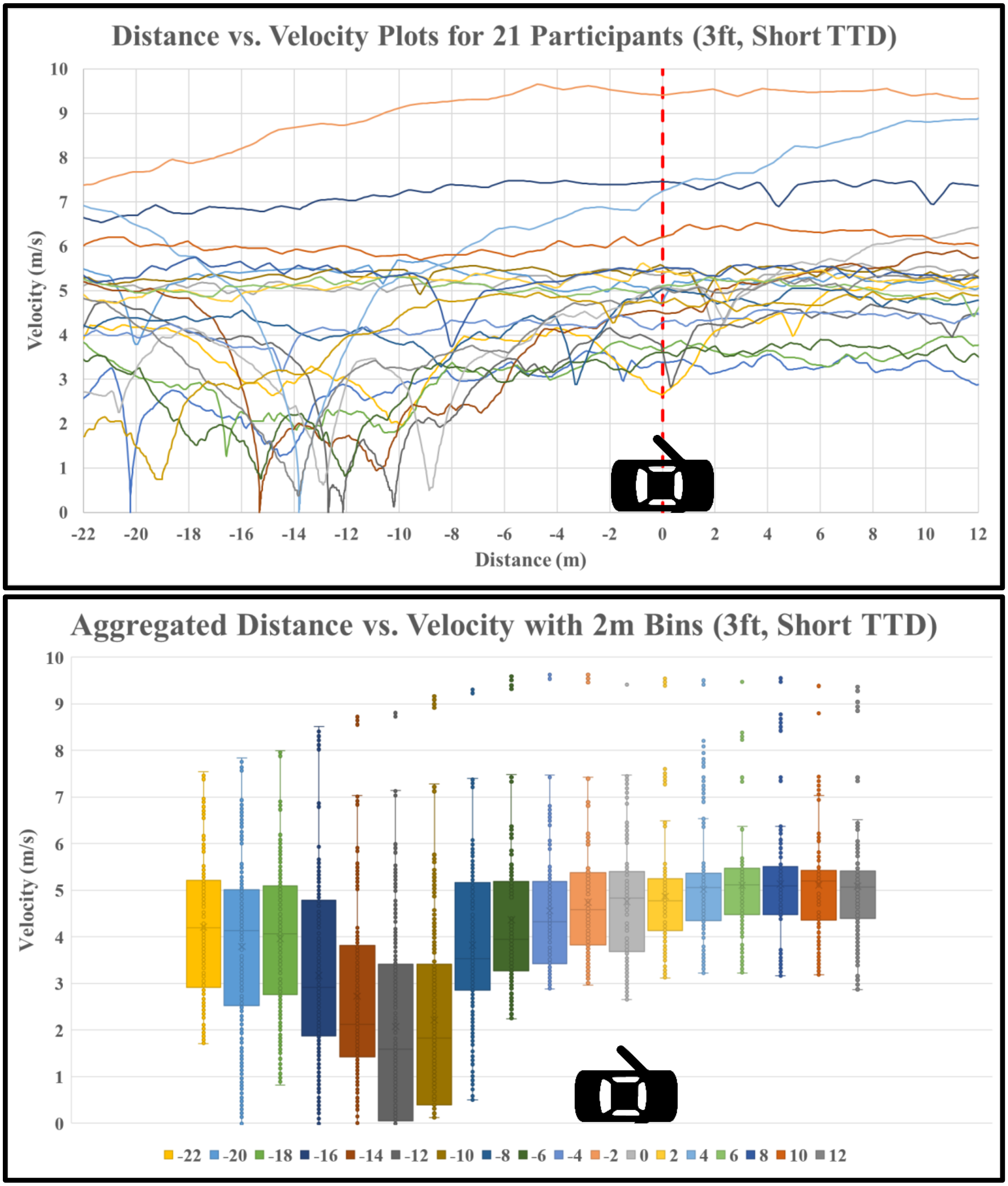


Figure 4.5 Bicyclist Velocity at Open Vehicle Door (3-foot effective bicycle lane width, short time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box*

[b]*Standard deviation denoted by bars extending above and below box*

[c]*Individual participant data denoted by dots*

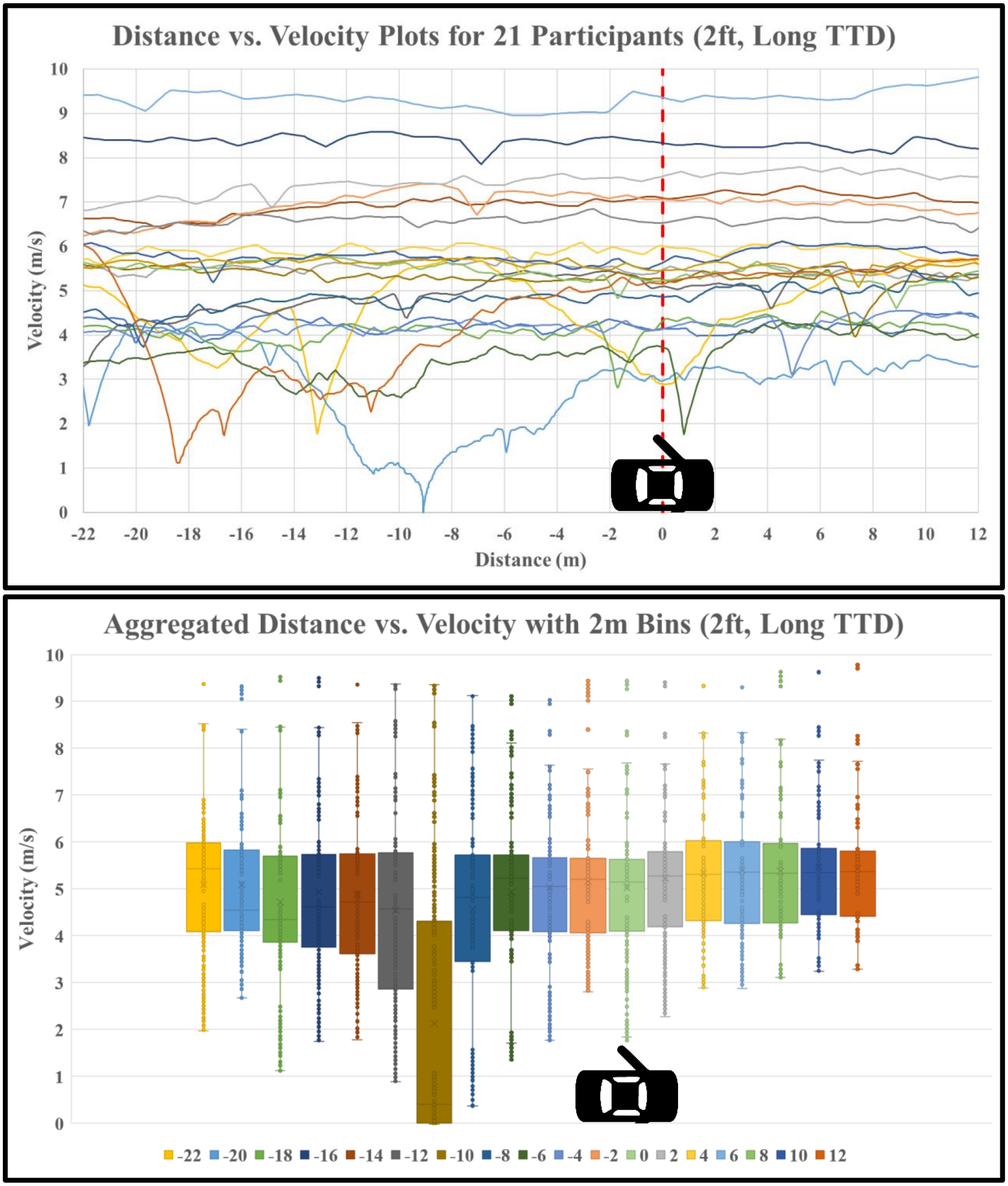
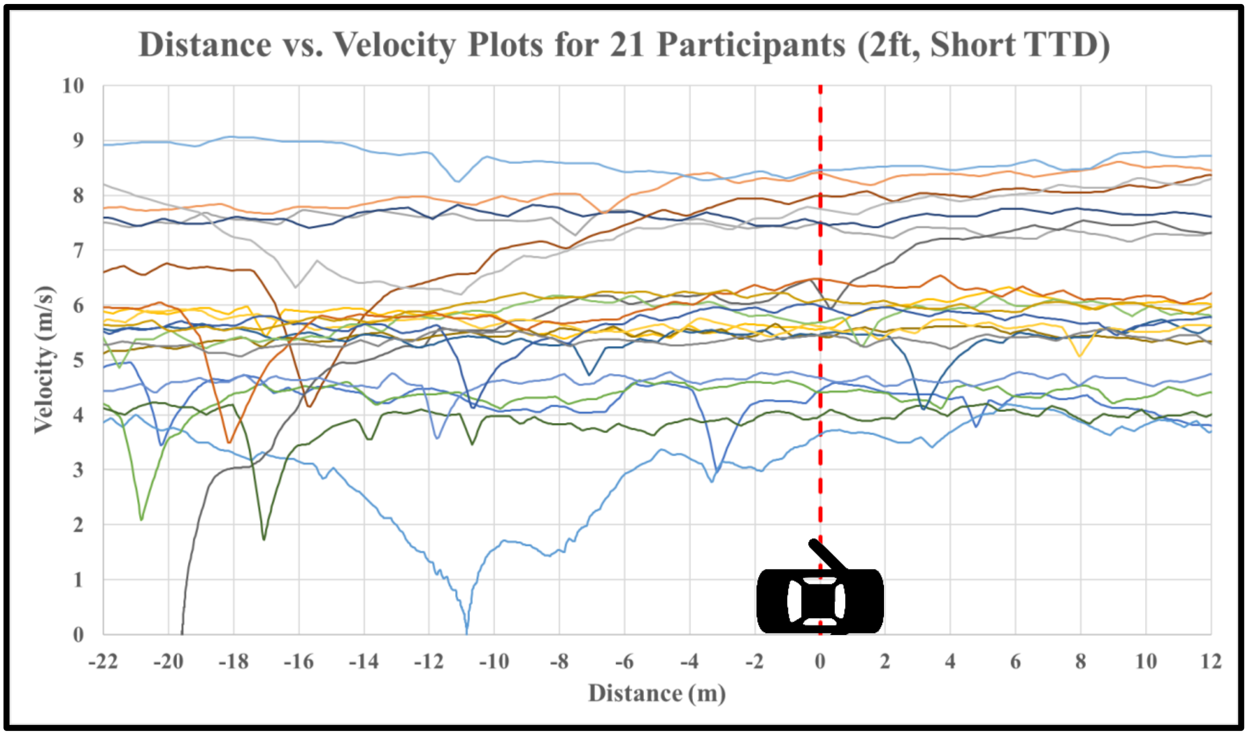


Figure 4.6 Bicyclist Velocity at Open Vehicle Door (2-foot effective bicycle lane width, long time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box*

[b]*Standard deviation denoted by bars extending above and below box*

[c]*Individual participant data denoted by dots*



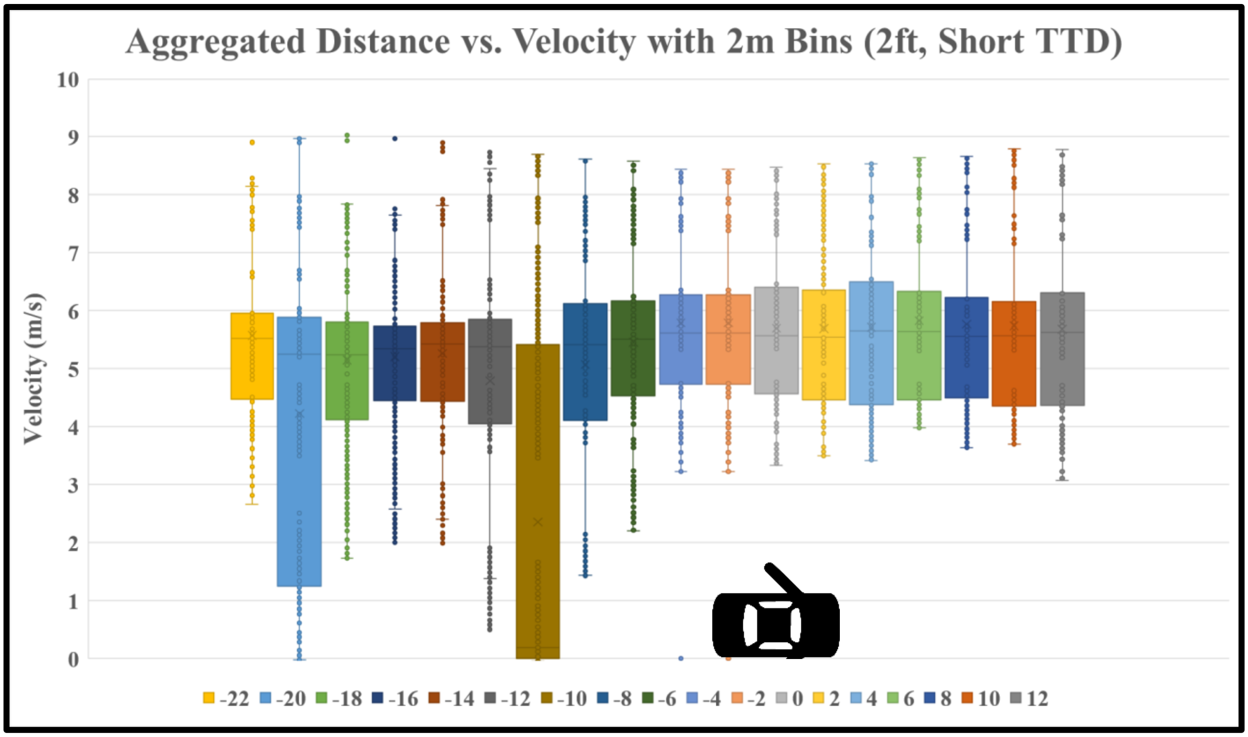


Figure 4.7 Bicyclist Velocity at Open Vehicle Door (2-foot effective bicycle lane width, short time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box*

[b]*Standard deviation denoted by bars extending above and below box*

[c]*Individual participant data denoted by dots*

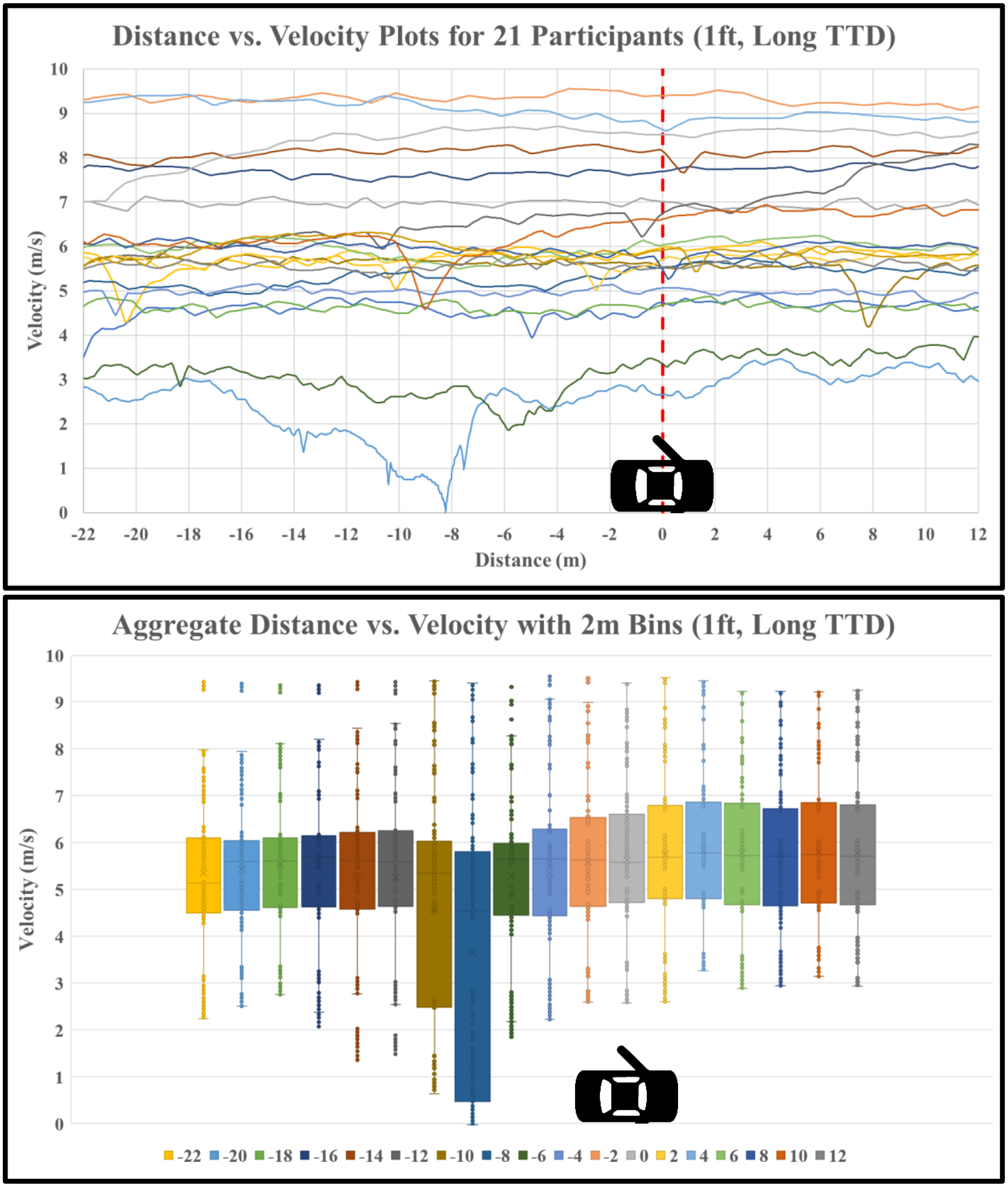


Figure 4.8 Bicyclist Velocity at Open Vehicle Door (1-foot effective bicycle lane width, long time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box*

[b]*Standard deviation denoted by bars extending above and below box*

[c]*Individual participant data denoted by dots*

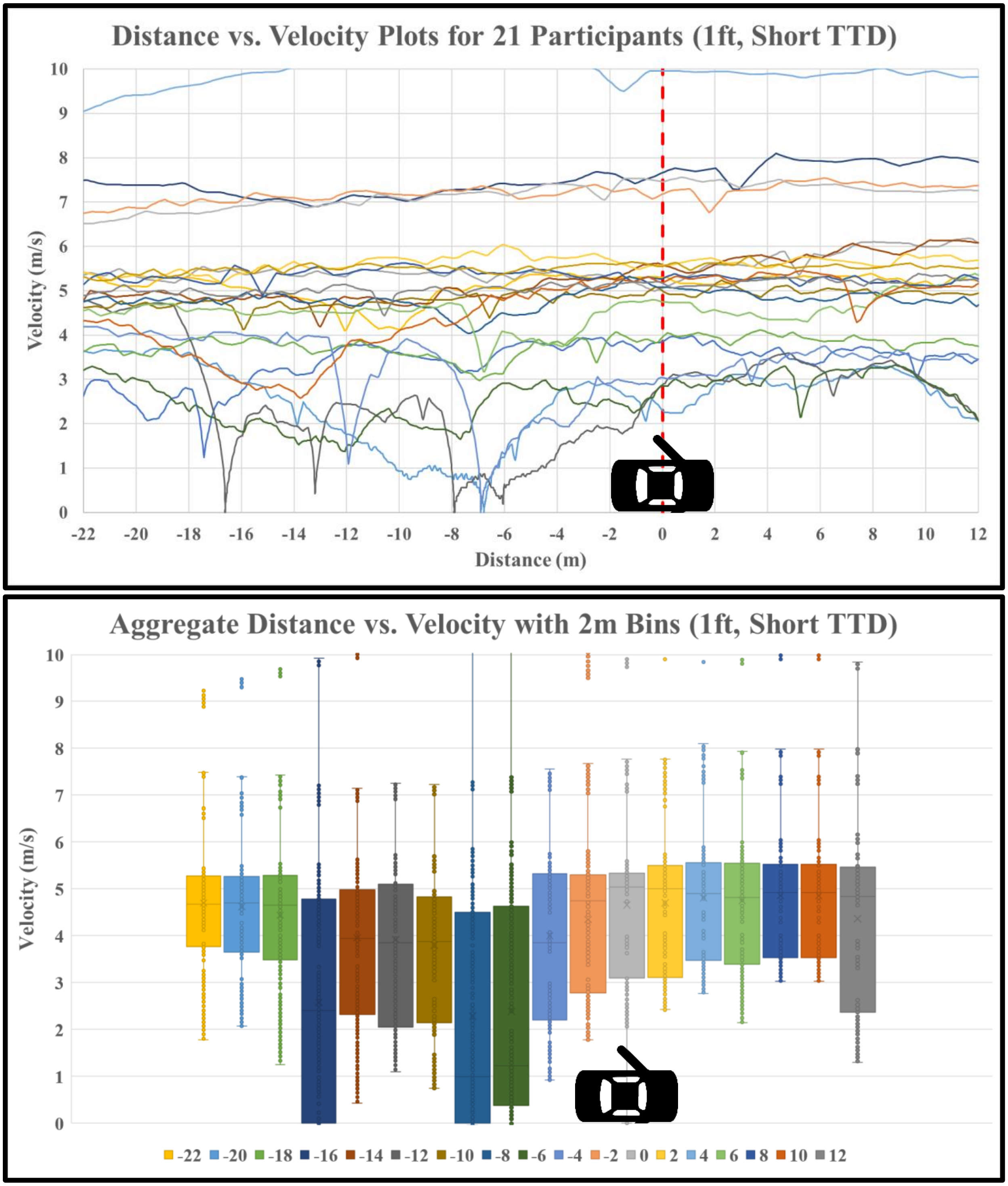


Figure 4.9 Bicyclist Velocity at Open Vehicle Door (1-foot effective bicycle lane width, short time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*

[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*

[c]*Individual participant data denoted by dots (bottom plot)*

4.2.2 Lateral Position

Mean, median, and standard deviation (SD) values for lateral position at each level of each within-subject variable are reported in Table 4.5. The mean and median values for each respective scenario are relatively close in value, suggesting balance in the data. Lateral position is measured with the right edge of the bicycle lane as the datum (e.g. a lateral position of 1.2 meters would be 1.2 meters to the left of the right edge of the bicycle lane facing the direction of travel). Bicyclists had the furthest lateral position from the right edge of the bicycle lane when given a long time to the open door and 1 foot of effective bicycle lane width with the vehicle door fully opened. Adversely, bicyclists had the lowest mean velocity when given a short time to the open door and 3 feet of effective bicycle lane width.

Table 4.5 Means and Standard Deviations of Lateral Position (m)

		1 ft. Width	**2 ft. Width**	**3 ft. Width**
Short TTD (0-5 seconds)	Mean	1.3	1.3	1.2 (min)
	Median	1.2	1.3	1.1 (min)
	SD	0.5	0.5	0.5
Long TTD (5+ seconds)	Mean	1.9 (max)	1.7	1.3
	Median	1.9 (max)	1.5	1.2
	SD	0.7	0.5	0.5

Two-way repeated measures ANOVA tests were used to determine effects of factors on mean bicyclist lateral position in each of the six door zone scenarios. A confidence interval of 95 percent was used. As shown in Table 4.6, the one-way interactions of time to the open door and width, as well as the two-way interaction of time to the open door × width, had significant effects on bicyclist lateral position. Figure 4.10 illustrates the statistically significant two-way interaction on bicyclist lateral position according to the two-way repeated measures ANOVA analysis.

Table 4.6 Two-Way Repeated Measures ANOVA Results on Velocity (m/s)

Source	F (degrees of freedom)	Significance	Partial Eta Squared
TTD	43 (1)	0.00	0.69
Width	22 (2)	0.00	0.53
TTD × Width	74 (2)	0.02	0.18

[a]*F denotes F statistic*
[b]*Statistically significant at 95% confidence interval*

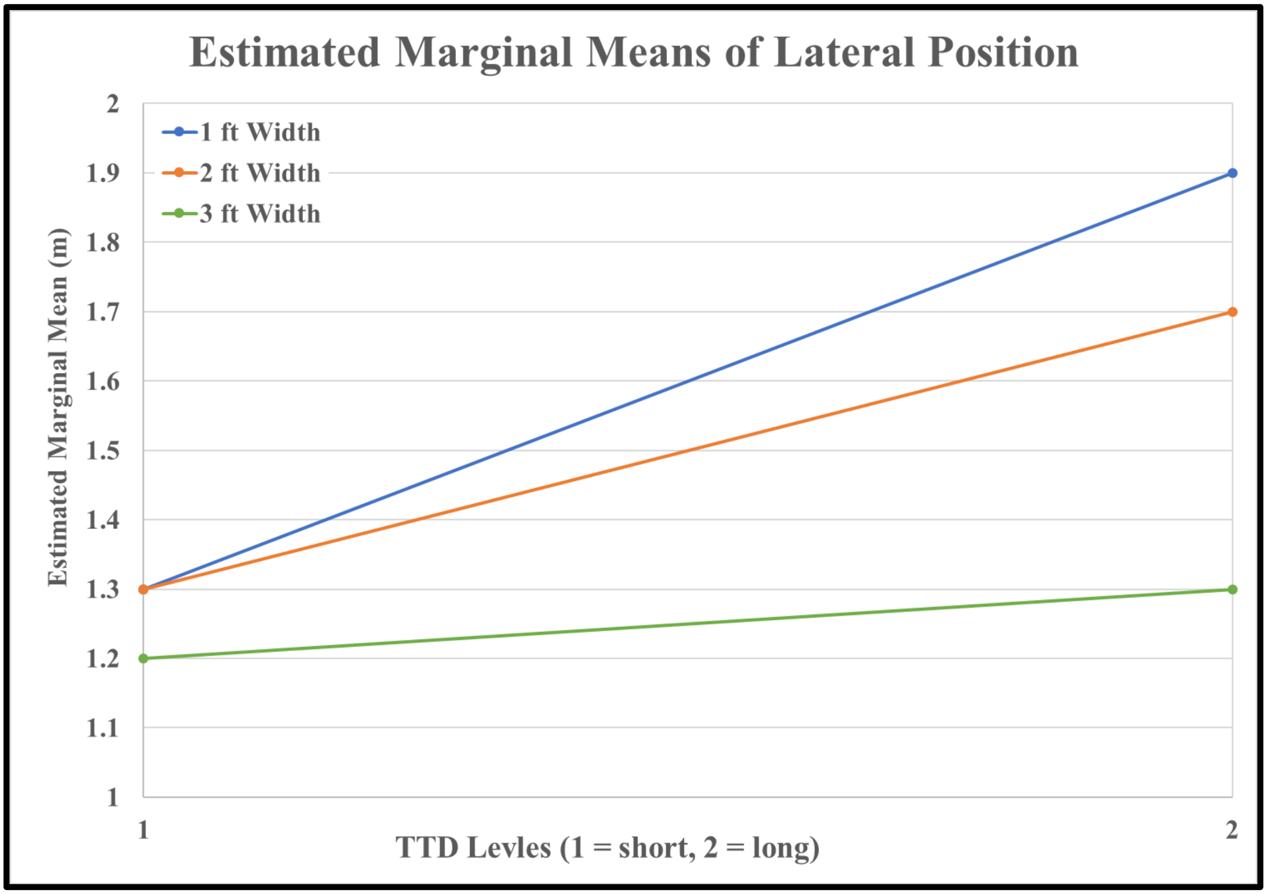


Figure 4.10 Graphical Representation of Two-Way Interactions on Lateral Position (m)

Figures 4.11 through 4.16 plot lateral position distributions for individual participants, and for the entire dataset aggregated at every 2 meters. Lateral position (meters) is plotted against distance along the bicycle lane (meters). The bicycle lane is denoted on the lateral position distribution for individual participants plots by solid, horizontal black lines at lateral positions of 0 meters (right bicycle lane line) and 1.8 meters (left bicycle lane line). The open vehicle door is at 0 meters in the following figures, and is denoted by a red dashed line in the lateral position distribution plots for individual participants. Plots at the top of each figure display lines for individual participant lateral positions. The aggregate plots (the plots at the bottom of each figure) display the mean (horizontal line inside box) and standard deviation (vertical bars extending above and below box) values at each 2 meters, which is overlaid on individual participant data (dots).

As illustrated by the figures, participants tend to ride outside of the bicycle lane for a greater distance when given a longer time to the open door versus a shorter time to the open door. It is also clear that the majority of participants choose to depart the bicycle lane when given 1 foot of effective bicycle lane width. It is important to note that individual participant plots that cross the line representing the open vehicle door (red dotted line) are not collisions—these occur when the participant decides to accelerate past the door before it has fully opened, or when the participant stops and waits for the vehicle door to close. The vehicle door closes approximately 20 seconds after it has been fully opened.

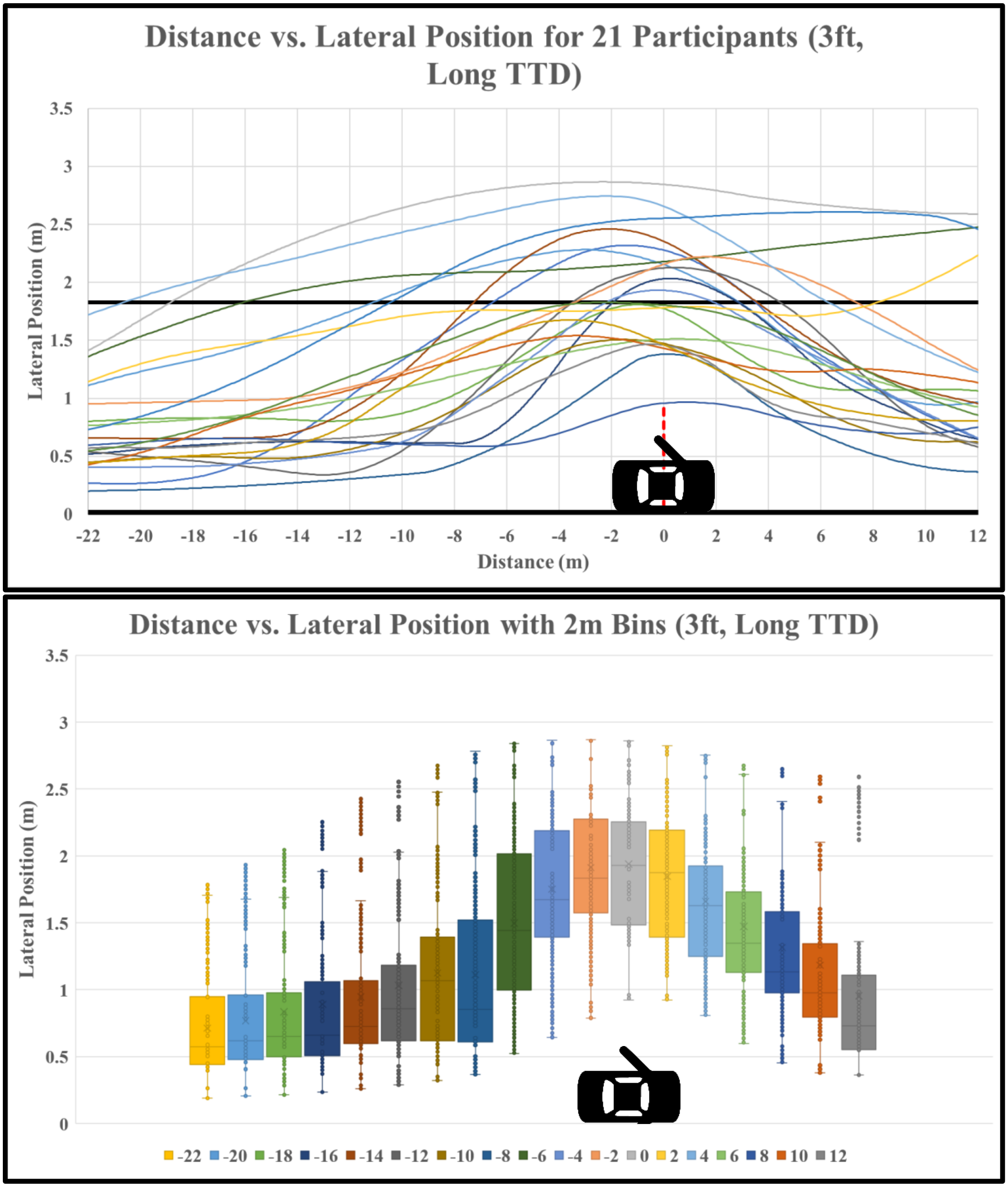
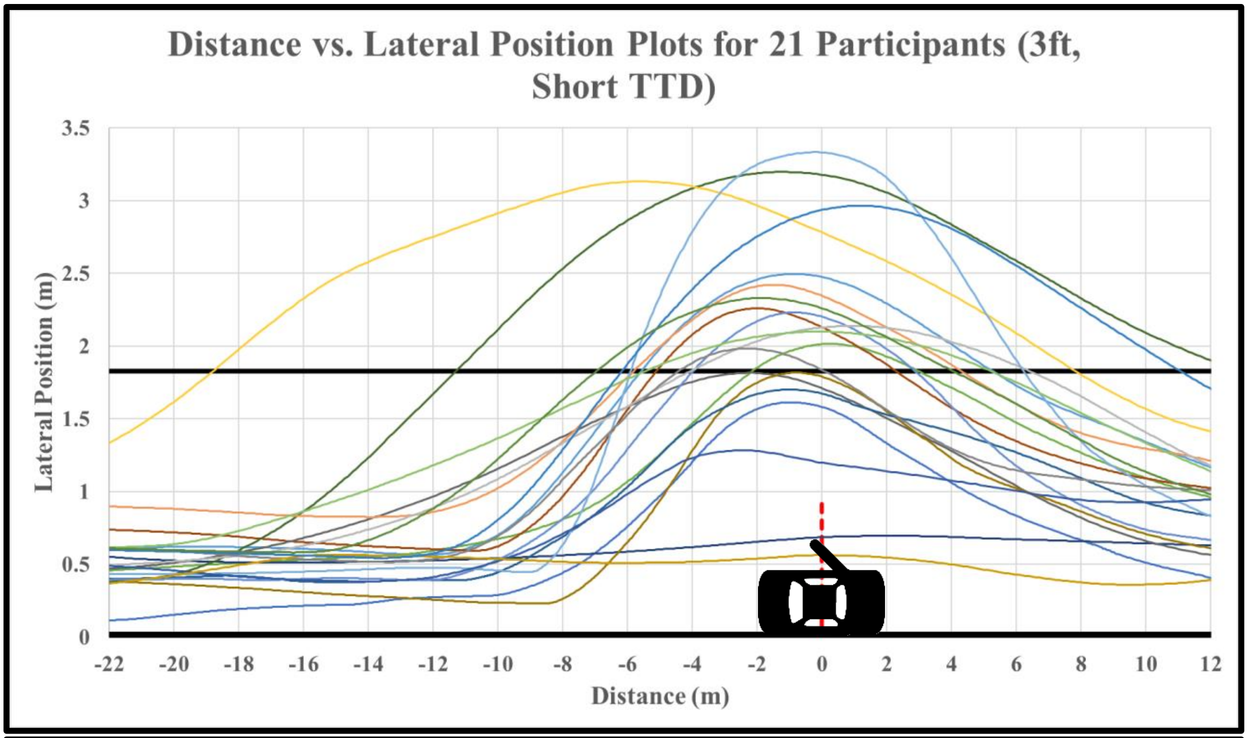


Figure 4.11 Bicyclist Lateral Position at Open Vehicle Door (3-foot effective bicycle lane width, long time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*
[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*
[c]*Individual participant data denoted by dots (bottom plot)*
[d]*Red dotted line represents distance open vehicle door extends into bicycle lane (top plot)*
[e]*Black horizontal lines represent left and right edges of bicycle lane*



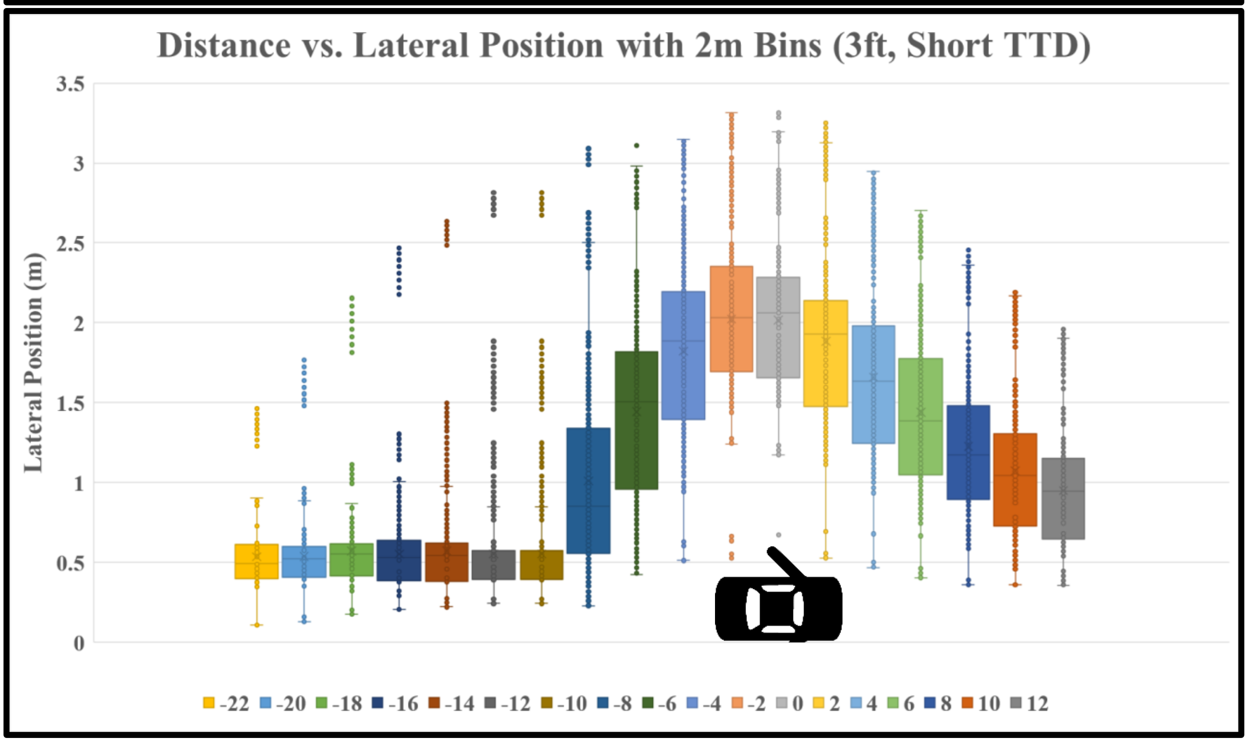


Figure 4.12 Bicyclist Lateral Position at Open Vehicle Door (3-foot effective bicycle lane width, short time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*

[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*

[c]*Individual participant data denoted by dots (bottom plot)*

[d]*Red dotted line represents distance open vehicle door extends into bicycle lane (top plot)*

[e]*Black horizontal lines represent left and right edges of bicycle lane*

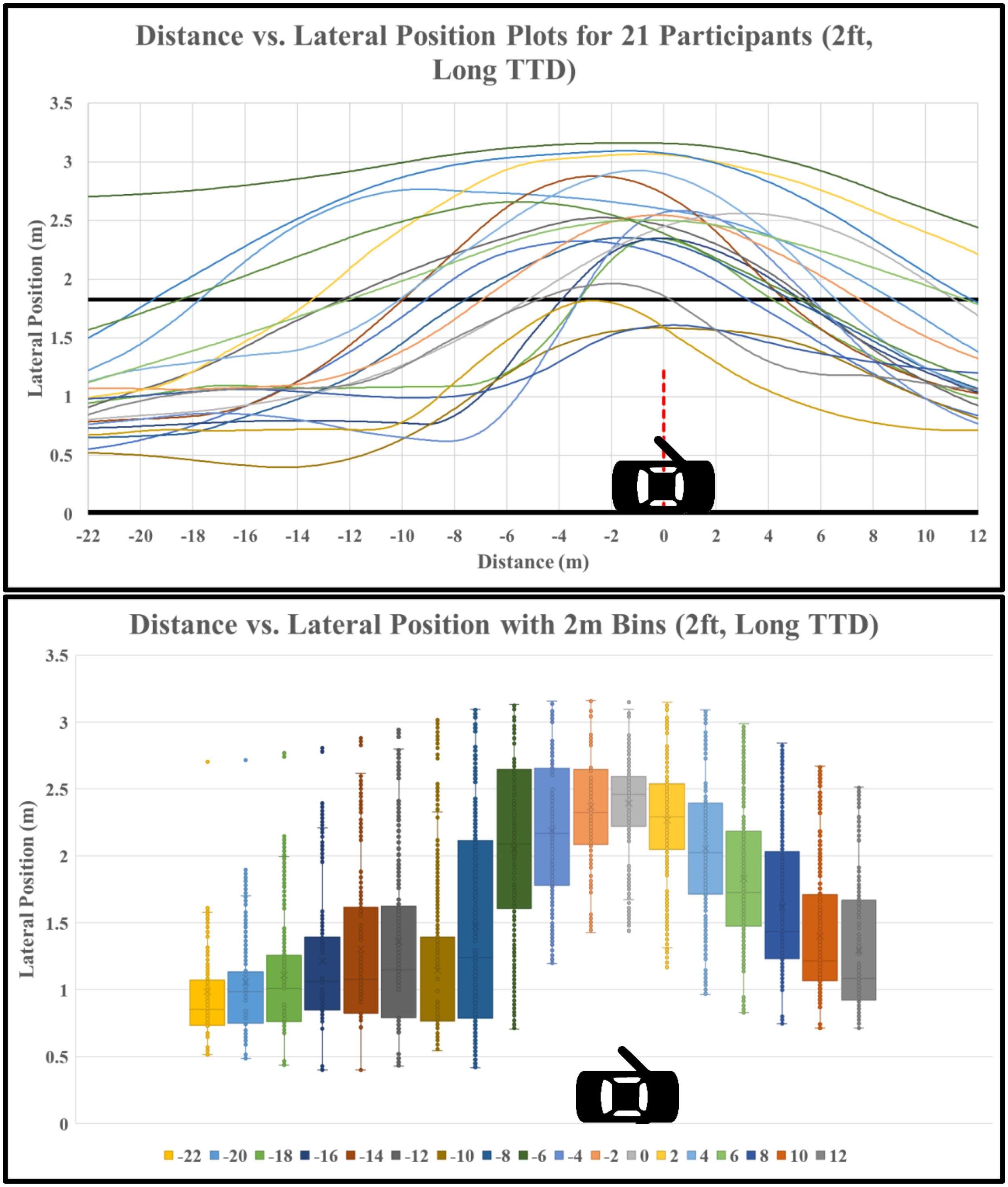


Figure 4.13 Bicyclist Lateral Position at Open Vehicle Door (2-foot effective bicycle lane width, long time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

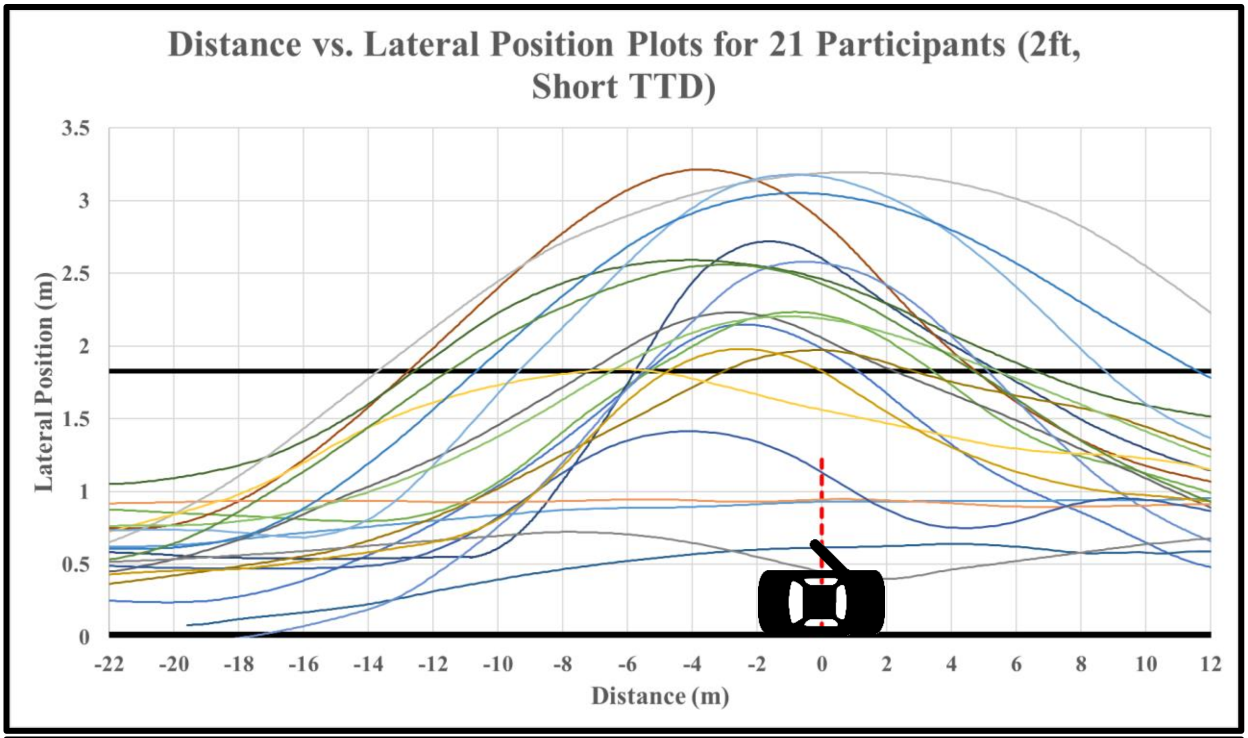
[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*

[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*

[c]*Individual participant data denoted by dots (bottom plot)*

[d]*Red dotted line represents distance open vehicle door extends into bicycle lane (top plot)*

[e]*Black horizontal lines represent left and right edges of bicycle lane*



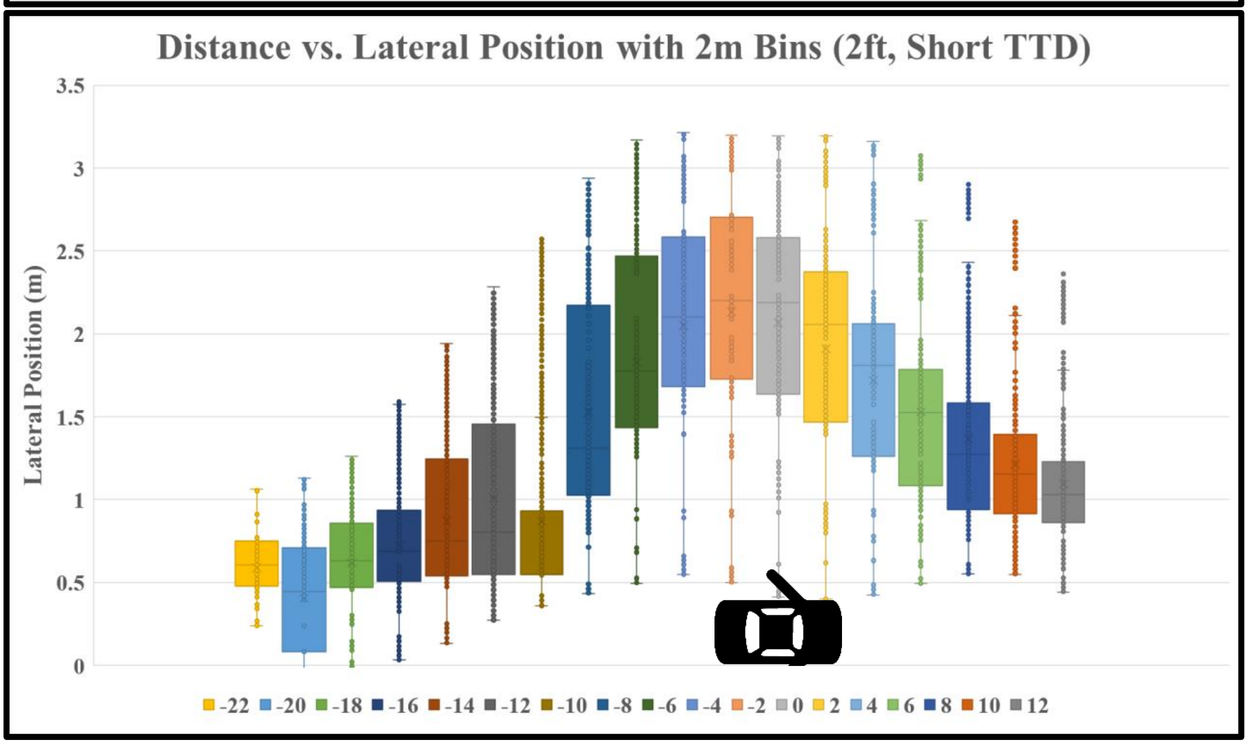


Figure 4.14 Bicyclist Lateral Position at Open Vehicle Door (2-foot effective bicycle lane width, short time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*

[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*

[c]*Individual participant data denoted by dots (bottom plot)*

[d]*Red dotted line represents distance open vehicle door extends into bicycle lane (top plot)*

[e]*Black horizontal lines represent left and right edges of bicycle lane*

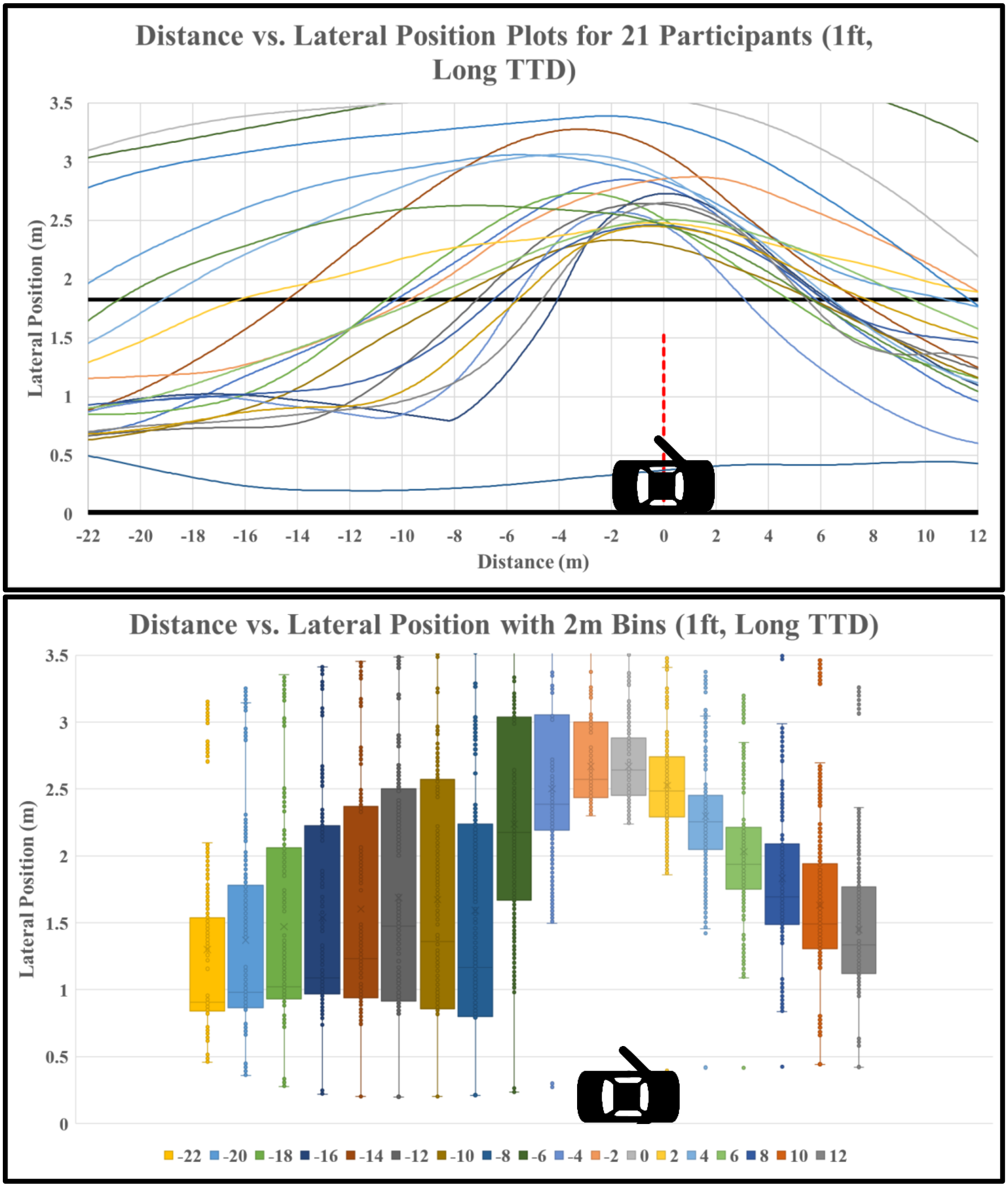
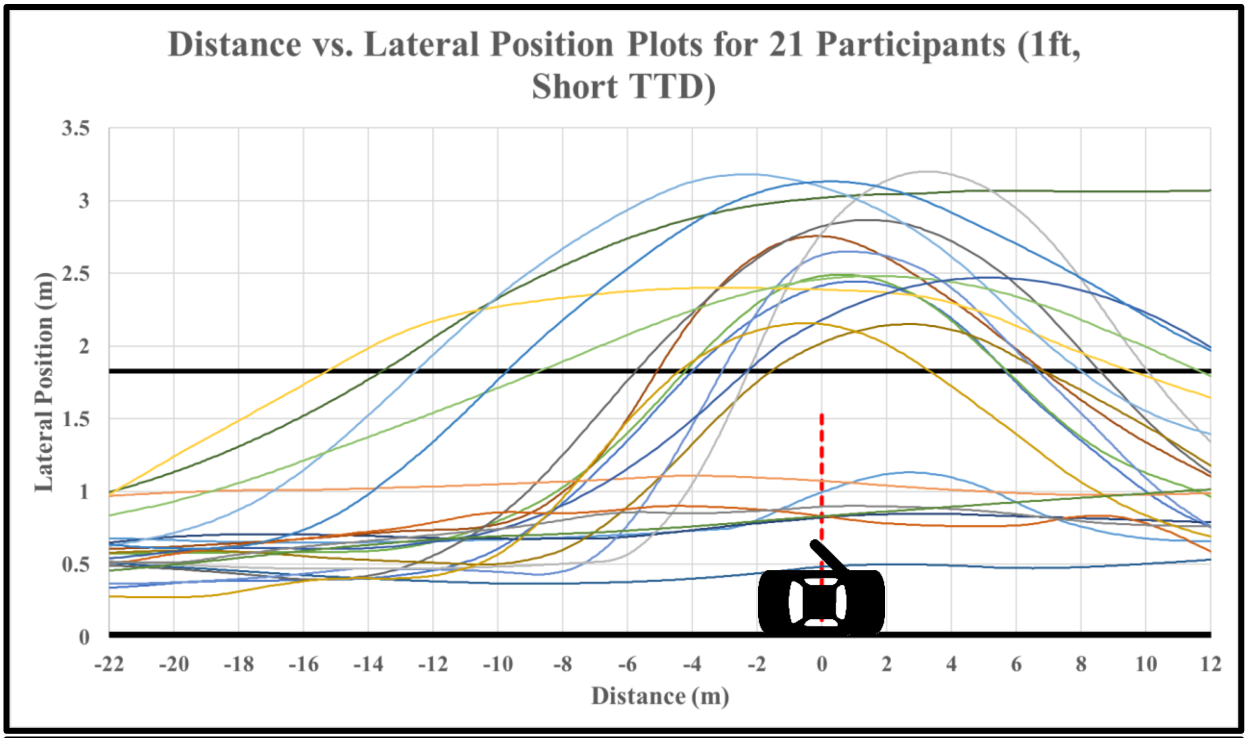


Figure 4.15 Bicyclist Lateral Position at Open Vehicle Door (1-foot effective bicycle lane width, long time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*
[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*
[c]*Individual participant data denoted by dots (bottom plot)*
[d]*Red dotted line represents distance open vehicle door extends into bicycle lane (top plot)*
[e]*Black horizontal lines represent left and right edges of bicycle lane*



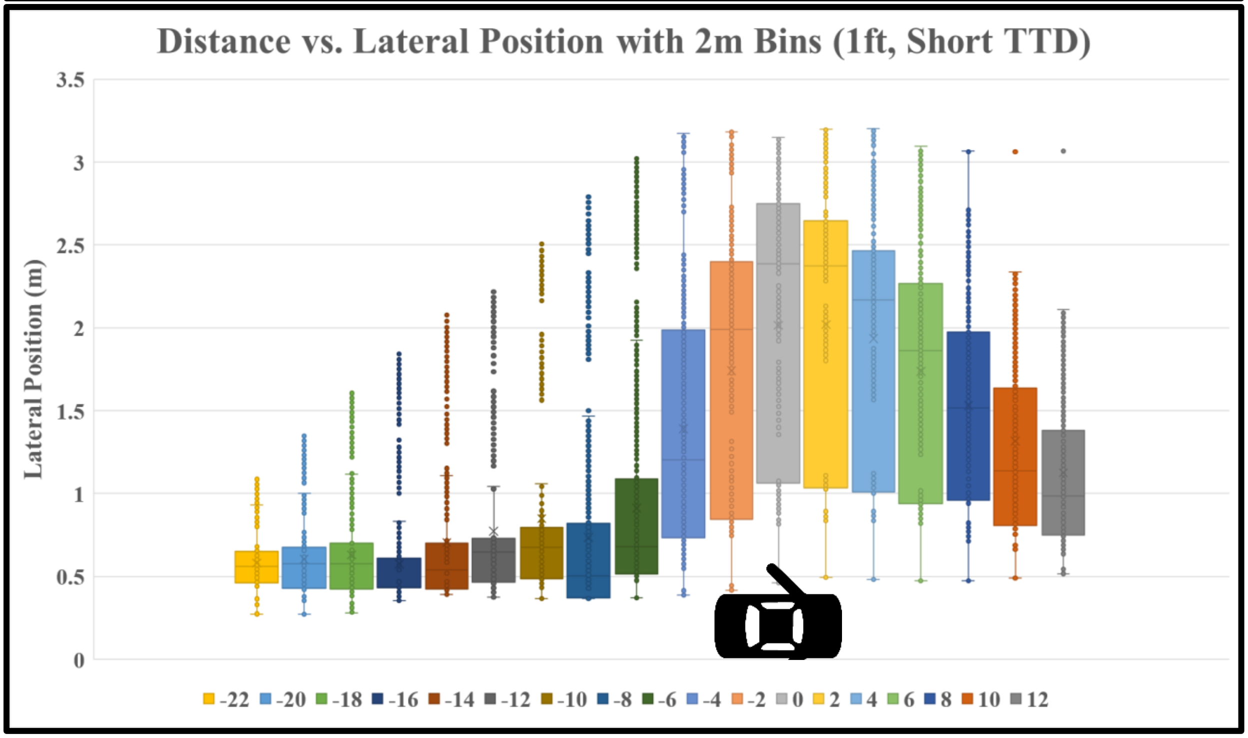


Figure 4.16 Bicyclist Lateral Position at Open Vehicle Door (1-foot effective bicycle lane width, short time to the open door) with Individual Plots (top) and Aggregated Plots (bottom)

[a]*Mean of each bin denoted by horizontal line in box (bottom plot)*

[b]*Standard deviation denoted by bars extending above and below box (bottom plot)*

[c]*Individual participant data denoted by dots (bottom plot)*

[d]*Red dotted line represents distance open vehicle door extends into bicycle lane (top plot)*

[e]*Black horizontal lines represent left and right edges of bicycle lane*

4.3 Selected Events

From the 126-total simulated door zone conflicts, zero collisions were observed and three near miss situations were observed. Each of these near miss situations occurred when the bicyclist was riding at a relatively high velocity, or when the bicyclist tried to accelerate past the opening vehicle door. Table 4.7 summarizes the characteristics of the three bicyclists who were involved in near miss situations. All near miss situations occurred in a scenario with a short time to the open door (0 to 5 seconds). Additionally, none of the participants in these cases had any experience with a door zone collision. Age and bicycling experience between participants in these cases vary, and do not show any trend.

Table 4.7: Characteristics of Bicyclists with Near Miss Situations

Case	**TTD (Width)**	**Gender (Age)**	**Bicycling Frequency**	**Riding Duration**	**Riding Purpose**	**Collision Experience**	**Near Miss Experience**
1	Short (1-Foot)	Male (68)	Less Than 1-2 Times a Month	20-30 Minutes	Recreation	No	Yes
2	Short (3-Foot)	Male (27)	1-2 Times a Month	Less Than 10 Minutes	Recreation	No	No
3	Short (3-Foot)	Female (19)	1-2 Times a Week	20-30 Minutes	Commuting	No	Yes

Figures 4.17 through 4.19 show captures from the simulated environment in these three cases. Captures from raw eye-tracking video data before and after the participant detects the opening vehicle door are also included in Figures 4.17 through 4.19. Based on the raw eye-tracking video data, it may be possible that in each case the participant was not actively searching vehicles parked in the adjacent parallel parking lane for potential opening vehicle doors. This may indicate that the participants in these cases detected the opening vehicle door later than other participants, and as a result had relatively less time and space to decide their action to avoid a collision with the

vehicle door. Actions chosen by the participants in these cases included a combination of changing their lateral position and accelerating. None of the participants chose to decelerate or stop.

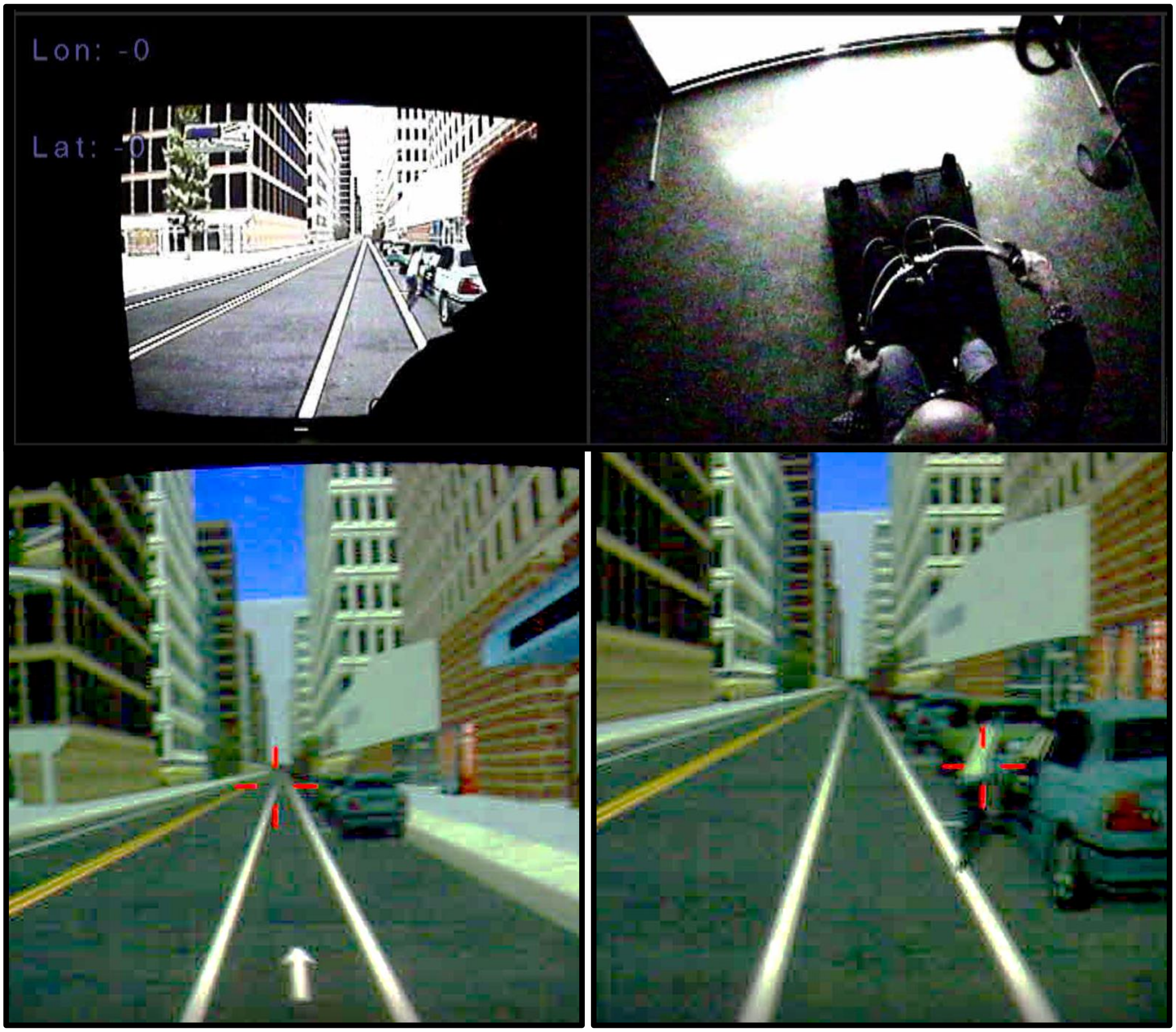


Figure 4.17: Near Miss Event 1 Observed in the Simulated Environment (top) with Raw Eye-Tracking Data Before (bottom left) and During (bottom right) Near-Miss Event

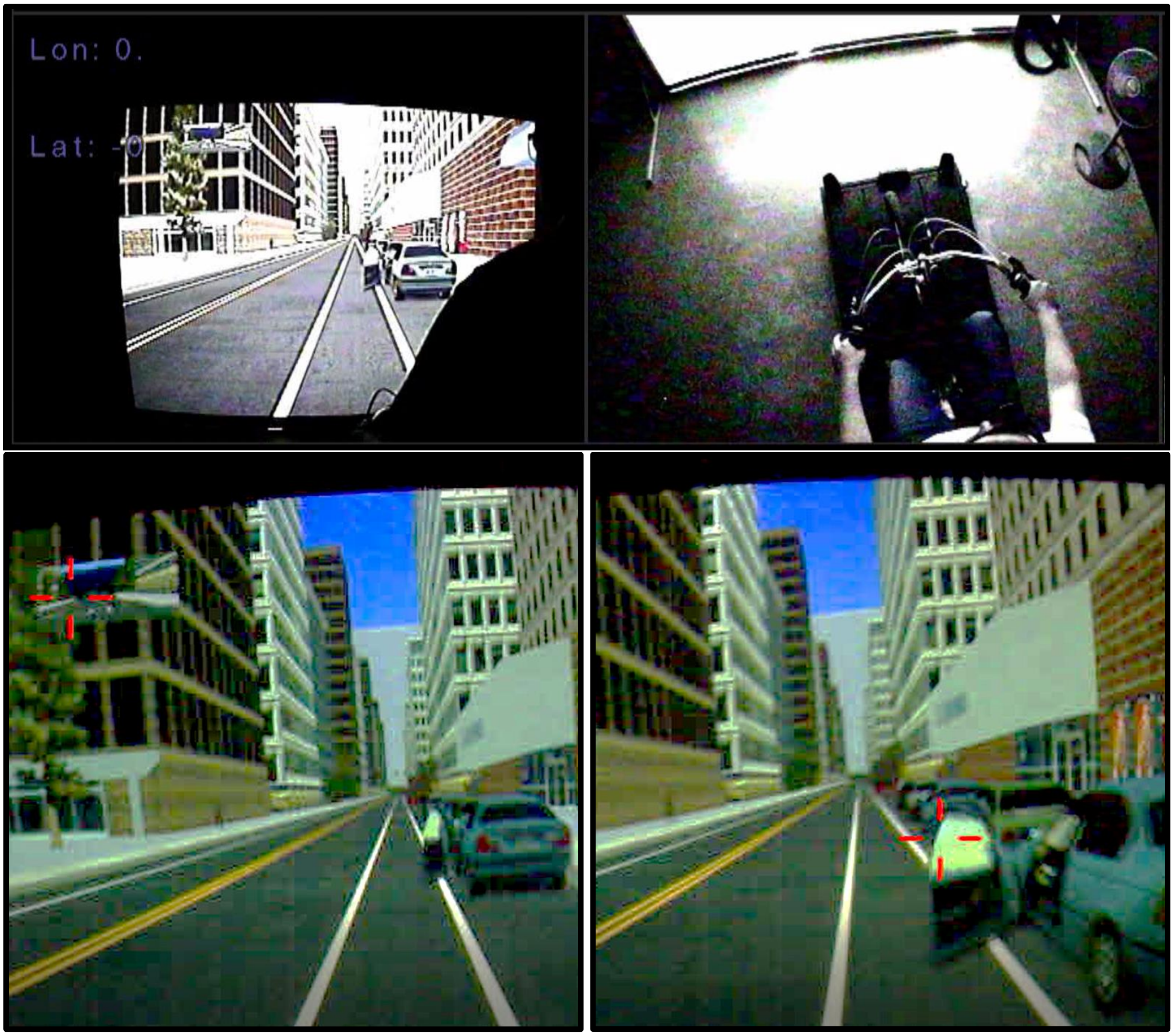


Figure 4.18: Near Miss Event 2 Observed in the Simulated Environment (top) with Raw Eye-Tracking Data Before (bottom left) and During (bottom right) Near-Miss Event

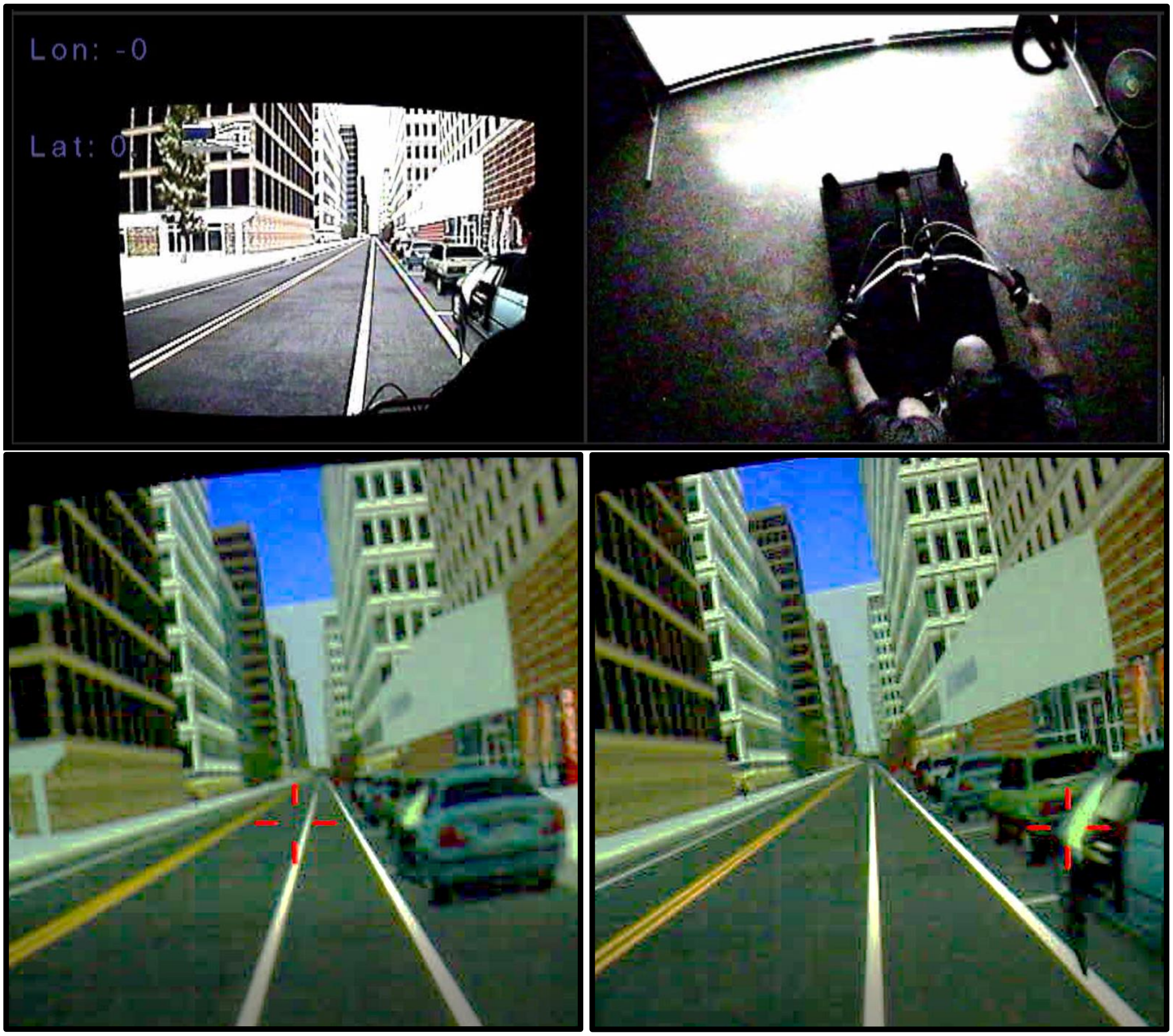


Figure 4.19: Near Miss Event 3 Observed in the Simulated Environment (top) with Raw Eye-Tracking Data Before (bottom left) and During (bottom right) Near-Miss Event

Table 4.8 summarizes the bicyclist performance in terms of velocity and lateral position in close proximity to the door zone during the each of the three near miss situations observed. These values are compared to the mean values from all the participants in the study. Note how in each case, the individual participants have mean velocities that are significantly greater than the mean velocities from the rest of the dataset. The individuals in the three cases also tended to ride slightly further away from the right edge of the bicycle lane when compared to the rest of the dataset.

Table 4.8: Bicyclist Performance during Bike-Truck Crash Events

Performance Measurement	Case 1	Case 2	Case 3
Maximum Velocity for Case (m/s)	6.2	8.9	5.3
Mean Velocity for Case (m/s)	5.5	5.0	5.2
Mean Velocity for Entire Dataset (m/s)	*4.9*	*3.4*	*3.4*
Maximum Lateral Position for Case (m)	1.1	1.3	2.0
Mean Lateral Position for Case (m)	0.66	0.68	0.95
Mean Lateral Position for Entire Dataset (m)	*0.54*	*0.48*	*0.48*

5 DISCUSSION

This chapter discusses the results of this study and their implications. The first section summarizes the major findings of the experiment. Additionally, recommendations for engineering treatments that would be effective in reducing the risk and severity of door zone collisions based on the findings of this study will be provided. The following sections discuss the limitations of this study and opportunities for future research related to door zone conflicts.

5.2 Bicyclist Performance

The survey results indicated that over one-third of participants had a high level of concern for door zone or door zone related collisions while riding their bicycle. Furthermore, over three quarters of participants had a moderate or high level of concern for door zone or door zone related collisions. However, few participants had experienced a collision with a vehicle door while riding their bicycle. More participants had experienced a near-miss situation with a vehicle door while riding their bicycle. This may indicate that door zone or door zone related collisions have a high perceived risk among bicyclists because of the prevalence of near-miss experiences, and not necessarily because of the prevalence of collisions.

5.2 Bicyclist Performance

The results of this study show some evidence towards a correlation between time to the open door, effective bicycle lane width, and bicyclist’s velocity and lateral position in close proximity to the door zone. Effective bicycle lane width alone did not show statistical significance in effecting a bicyclist’s velocity. Additionally, the results suggest that time to the open door and effective bicycle lane width have a greater effect on a bicyclist’s lateral position than they do on a bicyclist’s velocity.

The majority of bicyclists departed the bicycle lane when given only one foot of effective bicycle lane width. Therefore, it is possible that wider bicycle lanes are an effective solution to reducing the number of bicyclist who enter the motor vehicle travel lane when maneuvering around an open vehicle door. The study also found that bicyclists are more likely to depart the bicycle lane when given a shorter time to the open door. Furthermore, bicyclists who chose to depart the bicycle lane when given a longer time to the open door tended to remain outside of the bicycle lane for a greater distance when compared to the short time to the open door scenarios. Based on the results of this study, the most effective solution to preventing door zone or door zone related collisions would be a combination of treatments that increase potential times to collision and increase bicycle lane widths.

Behavior observed by participants in this study can be categorized into two general reactions when in close proximity to the door zone: those who reduce their velocity or come to a stop before the open vehicle door, and those who increase their velocity while passing the open vehicle door. More stopping and slowing behavior was observed in scenarios with shorter times to the open door. Small dips in individual velocities were also more common in scenarios with shorter times to the open door. These small dips in velocities may be due to hesitations in participants as they decide which course of action will be safest. This indicates that there is a dilemma zone when a bicyclist is confronted with a door zone conflict.

Participants who chose to accelerate past the open vehicle door were at greater risk of entering a near-miss scenario or collision. The occurrence of this higher risk behavior was more common in scenarios with shorter times to the open door. This is especially evident when comparing the long and short times to the open door for the one-foot effective bicycle lane width scenarios. The contrast between these two scenarios may provide further evidence of a dilemma zone when a bicyclist is confronted with a door zone conflict.

5.3 Recommendations

Based on the results of this study, buffered bicycle lanes may be an effective engineering treatment to reduce the risk and severity of door zone or door zone related collisions. Most existing designs for buffered bicycle lanes provide additional space between the bicycle lane and motor vehicle travel lane. An example of this design is the buffered bicycle lane design outlined in the National Association of City Transportation Officials (NACTO) (Figure 5.1). Other variations of buffered bicycle lanes offer bicyclists additional space between both the motor vehicle travel lane and adjacent on-street parallel parking. An example of this arrangement from Portland, Oregon is also shown in Figure 5.2. In this design, the bicycle lane is also made narrower to encourage bicyclists to ride at slower velocities. It is important to note that buffered bicycle lanes require additional real estate, and may not be a practical solution for all roadways.

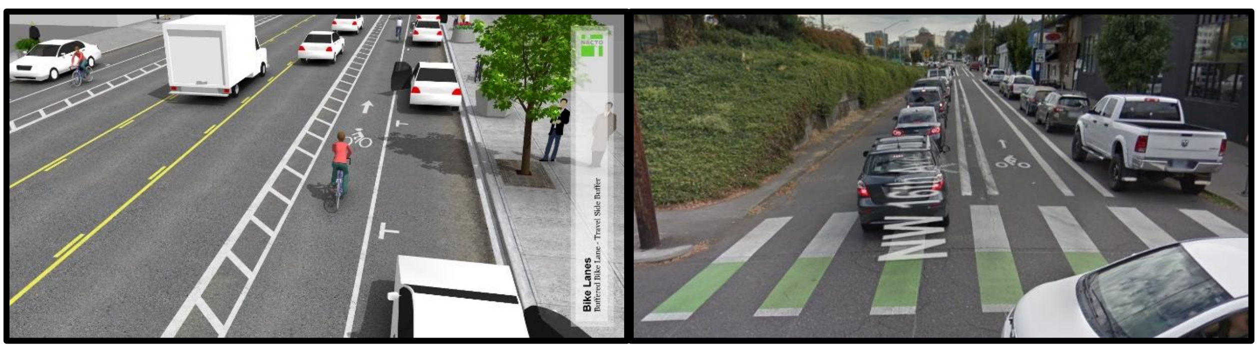


Figure 5.1: Example Design of Buffered Bicycle Lane from NACTO (left) (NACTO, 2011) and a Variation of a Buffered Bicycle Lane in Portland, OR (right) (Google Maps, 2018)

Another potential engineering treatment for door zone or door zone related collisions is contra-flow bicycle lanes (Figure 5.2). Bicyclists using contra-flow bicycle lanes travel in the opposite direction of both motor vehicle traffic and on-street parallel parking. Potential door zone collisions would occur between a bicyclist and the outside of a vehicle door (as opposed to the inside). This may reduce the severity of door zone collisions by allowing the vehicle door to close back on the vehicle if hit by a bicycle. Drivers in parked vehicles adjacent to contra-flow bicycle lanes also have a better line of sight for detecting approaching bicyclists.

Figure 5.2: Example of a Contra-Flow Bicycle Lane in Chicago, IL (NACTO, 2011)

Further work should be done to develop new engineering treatments or test the effectiveness of existing engineering treatments in increasing times to the open door, potentially by reducing bicyclist velocities or by providing additional warning to drivers or bicyclists of an impending crash. Potential engineering treatments that could reduce bicyclist velocity include bicycle traffic calming devices before or throughout stretches of bicycle lane adjacent to on-street parallel parking. Signage warning bicyclists of potential door zone conflicts could also be effective in reducing bicyclist velocities and increasing bicyclist caution.

5.4 Limitations

The following are the primary limitations of this study:

- The range of time to the open doors between the bicyclist and the open vehicle door was relatively large. The simulation was calibrated to the participant's average riding velocity to minimize the spread of this range.
- 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 they become tired or less focused. The order of the scenarios was partially randomized, and the duration of the test drives were relatively brief to minimize these effects.
- The visual display of the bicycling simulator used in this study did not provide a peripheral field of view for participants. While peripheral vision was limited, a small window was placed on the top left corner of the screen, providing a rear-view for bicyclists.

5.5 Future Work

Additional research is needed to continue to explore the critical safety issue of door zone collisions. The following are potential research threads that would augment this study and further expand the topic of how bicyclist behave in the door zone.

- Another statistical measure should be considered to encompass variables that the two-way repeated measures ANOVA could not (e.g. a regression model that takes into account participant bicycling experience).
- The research gathered eye-tracking data from participants. From this data, average fixation durations, dwell durations, and visual attention during unique selected events can be analyzed.
- Shorter time to the open doors could provide a higher rate of collisions and near miss events.
- Bicyclist behavior in the door zone with different engineering treatments (e.g. buffered bicycle lanes, green pavement marking, signage) could be considered.
- Incorporating different vehicle doors, such as truck doors or SUV doors.

- Incorporating different environmental factors, such as varying adjacent parking densities and traffic volumes.

6 CONCLUSION

This chapter will revisit the research questions, goals, and hypothesis developed in the Methods chapter, and assess each based on the results of this study. The second section of this chapter will state recommendations for future directions of research based on the findings of this study.

6.1 Revisiting Research Questions, Goals, and Hypothesis

Each of the three research questions were answered by this study. The time to the open door and remaining amount of space in a bicycle lane with an open vehicle door does influence bicyclists' lateral position, velocity, and acceleration. It was found that generally, time to the open door had a greater effect on the dependent variables than effective bicycle lane width.

The specific goals associated with this research study were also accomplished. Some additional information on the perceived risk of door zone or door zone related collisions among bicyclists was found through the post-ride survey. Lateral position, velocity, and eye-tracking data was also collected from participants as they were exposed to six door zone scenarios. Furthermore, based on the results of this study the threshold where all participants decided to depart the bicycle lane was identified as one foot of effective bicycle lane width. More participants decelerate in short time to open door scenarios when compared to long time to open door scenarios. Finally, these findings were used to suggest buffered bicycle lanes as a potential solution to reducing the risk and severity of door zone or door zone related collisions.

The hypothesis was partially proven by the results of this study. Participants were more likely to decelerate when faced with a shorter time to open door, however more participants chose to accelerate past the opening vehicle door when given a smaller effective bicycle lane width. Participants were more likely to maintain their velocity when given a longer time to open door and larger effective bicycle lane width. Finally, participants were more likely to depart the bicycle lane when given a smaller effective bicycle lane width, but were also more likely to depart the bicycle lane when given a shorter time to open door.

6.2 Next Steps

Based on the results of this study, future work building off this study could take two logical directions, and are listed below:

1. Position, time, and velocity data from this study should be run through a regression model to identify how other factors influenced bicyclist behavior inside or in proximity to the door zone (e.g. bicyclist experience). Eye-tracking data collected during this study should be analyzed to better understand the reasoning behind participants' behavior observed in this study. The effect of various engineering treatments on bicyclist behavior inside or in proximity to the door zone should be studied.
2. Driver behavior when opening a vehicle door adjacent to a bicycle lane should be evaluated, potentially by utilizing a driving simulator. Bicyclist behavior observed in this study can be used to create more realistic models for bicyclists in the simulated environment which the driver is interacting with. The effect of various engineering treatments on driver behavior when opening a vehicle door adjacent to a bicycle lane should be studied.

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