VALIDATION OF A VIRTUAL REALITY BICYCLE SIMULATOR TO ASSESS PERCEIVED SAFETY OF CYCLISTS

A Dissertation Proposal Submitted to the
Department of Engineering Systems and Environment
University of Virginia

In Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy

by
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December 2021

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ACKNOWLEDGEMENTS

First and foremost, I have so much gratitude for my wonderful advisor Dr. Donna Chen. Dr. Chen and I both started at UVA in the fall of 2015, and I have thought countless times since then how lucky I was to get placed under her advisement for my master's degree that year. I have no doubt Dr. Chen is the reason I have enjoyed research, why I have been supported through grad school with an incredibly smart and talented research group, and why I ultimately carried on for a PhD. Thank you so much for all of your advice and guidance over the years, nothing else has been more consequential in my success in reaching this point.

In addition to the guidance of Dr. Chen, I have been fortunate to lean on the support of many other mentors during my time at UVA. A special thank you to my committee Dr. Michael Fontaine, Dr. Brian Smith, Dr. Arsalan Heydarian, and Dr. Andrew Mondschein. And I want to express my gratitude to my COVES mentor Ann Phillips and Christine Mirzayan mentor Dr. Katherine Kortum for helping me gain valuable experience that enabled me to envision life beyond grad school, and motivate me towards the PhD finish line.

This dissertation would not have been possible without the Omni-Reality and Cognition Lab members, Dr. Chen, Dr. Heydarian, freshly minted Dr. Austin Angulo and Xiang Guo. It has been quite the ride, starting a lab from scratch, during a pandemic no less. Thank you for all your support over the years and for making many hours in the lab so much fun.

I also want to extend a huge thank you to my incredible circle of friends who have made graduate school an absolute blast and a life changing chapter of my life. Graduate school is an unusual time where close friends come and go in terms of proximity, but I have every confidence that these friendships will endure in longevity. You all have helped me to grow as I navigated ups and downs and I appreciate all the support you have given me. Thank you to all my hometown friends who never fail to make time to catch up during my visits home. Your friendship means the world to me.

Finally, I cannot express enough gratitude to my parents, my siblings Dan, Andrew, and Hayley, my partner Alex, and the rest of my family. I am so lucky to have the most loving and supportive family around me. And a special thank you to my grandfather Charles Mathys, for inspiring me to be an engineer many years ago, leading me down this winding path to my PhD.

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ABSTRACT

Rising cyclist fatalities in the US necessitate innovative methods to study cyclist safety. Virtual reality (VR) technology has advanced significantly in recent decades, leading to commercially available, highly realistic, and cost-effective VR head mounted displays (HMD). Virtual reality bicycle simulators allow researchers to collect stated and revealed preference data using easily modifiable virtual environments, while keeping participants in a controlled and safe environment. This is a potential solution to drawbacks of traditional research methods and existing data sources (such as crash and survey data). Crash data, which is largely geared towards motor vehicles, excludes information that would be useful for studying cyclist safety (e.g., bicycle infrastructure at crash site, safety equipment such as lights and reflectors, helmet use, etc.). Bicycle crashes are also highly underreported in crash databases. While surveys are a cost-effective method to reach large populations, particularly when distributed online, they are subject to hypothetical bias and individual interpretation, and cannot provide the kind of immersive visualization afforded by VR.

Bicycle simulators exist in labs worldwide, and range from basic (i.e., using a keypad to move a bicyclist forward on a screen) to technologically advanced (i.e., physical stationary bicycle used by the research participant that can record steering, braking, and speed, with visualization across multiple screens or via a VR HMD). This dissertation discusses the design and implementation of a state-of-the-art VR bicycle simulator in a new lab (the Omni-Reality and Cognition Lab [ORCL] at UVA). This dissertation also describes the validation of the simulator against real world cyclist behavior and using the simulator to assess cyclists' perceived safety under different bicycle infrastructure scenarios.

While VR allows for a controlled, low-risk environment for repeatable experimentation, established methods for validating bicycle simulators for transportation research currently do not exist. This study validates a bicycle simulator which allows users to pedal, steer, and brake on a stationary bicycle trainer while wearing a VR headset. A replica virtual environment is created from the Water Street corridor in Charlottesville, Virginia. Then, simulator user behavior (N=50) is benchmarked against real world cyclist behavior (N=90) collected from video footage of Water Street. Absolute validity of speeds between the participants in the VR environment and cyclists in the real-world corridor was verified. VR research participants also reported via stated preference surveys their perceived realism about various aspects of the simulator. Results from the survey show that 94% of participants felt the simulator was immersive and 70% felt the VR environment was consistent with their real-world cycling experiences. This research presents a framework for validating a VR bicycle simulator, a critical first step to confirm the capabilities of VR simulation for bicycle transportation research.

Perceived safety of vulnerable road users can be studied using VR simulators to reproduce real-world-like behaviors, while concurrently collecting SP data. This study uses the VR bicycle simulator and instructs participants to ride through three different immersive virtual environments where all settings are identical except the bicycle infrastructure type (sharrows, bike lane, and protected bike lane). The sharrows environment is a replica of the as-built conditions of the real-world corridor against which the simulator has been benchmarked. Using data from post-experiment surveys, it was found that overall, participants (N=50) felt significantly safer in bike lanes and protected bike lanes compared to the sharrows, but the effect is nuanced based on gender. Female cyclists found both the bike lane and protected bike lane to significantly increase safety compared to the sharrows, while for male cyclists, only the bike lane was reported to feel significantly safer than the sharrows. When examining cyclist perceptions across two vehicle volume levels, no statistically significant difference in perceived safety was found. Some behavioral differences were observed across the three environments; cyclist speeds were lower in the protected bike lane than in the bike lane or as-built environments and standard deviation of distance to the curb is significantly lower in the protected bike lane and bike lane environments than in the as-built environment. These results indicate that bicycle infrastructure can meaningfully impact cyclist's physical location and movement. This study demonstrates the potential for using VR simulation for understanding cyclist

perceived safety on various bicycle infrastructure types, which may be especially valuable when evaluating new and unfamiliar infrastructure designs.

CHAPTER ONE: INTRODUCTION

1.1 MOTIVATION

Studying cyclist safety is critical to move towards a more equitable, environmentally friendly, healthy, and safe transportation network. Cyclist fatalities have risen recently, with 846 cyclist fatalities in 2019. Cyclist fatalities have not fallen below 800 since 2014 when 729 deaths were recorded. (*Fatality Analysis Reporting System, 2021*). Recent years have also seen increases in automobile deaths, although long term trends over several decades still indicate a decline, largely due to advances in technology (automatic breaking, automated cruise control, lane keeping, airbags, seatbelts, etc.). For cyclists, improved safety features do not present the same opportunity as with cars. Bicycle helmet design has improved, by incorporating additional elements that reduce rotational forces on the head which can result in traumatic brain injury. The commercially available Multi-Impact Protection System (MIPS) being one of them. However, lacking other opportunities for technological advances, in order to keep cyclists safe, transportation engineers, planners, and others have to rely on improving safety through infrastructure, roadway design, education, and increasing mode share.

Many cities around the world are pushing for initiatives like Vision Zero, which imagines zero transportation-related deaths. As the world moves through the COVID-19 pandemic, many cities may consider making temporary transportation changes permanent to accommodate changing preferences. Cities large and small across the US have established car-free streets, created space for more social distancing and outdoor dining, and added bike lanes as people shy away from public transit *("Healthy Streets", 2020; "Staunton", 2020; "Photos", 2020, "City Council", 2020; "New", 2020*). Rebuilding habits and priorities post-pandemic allows planners to think critically about how public roads are utilized. Biking is a mode of transportation with obvious benefits (environmental, congestion, health) and cities with high rates of bicycling have a lower risk of fatal crashes across all modes of transportation (*Marshall & Garrick, 2011*). Better safety outcomes have been found in locations with an increased prevalence of bicycle facilities and dense road networks with lower speeds (*Marshall et al., 2018*). If cities are designed to make the most vulnerable road users feel safe, the effects will be felt by everyone.

Numerous interventions can be undertaken to improve the safety of vulnerable road users. In a study comparing the United States to Sweden (where the concept of Vision Zero originated), the main recommendations to improve cyclist safety were to separate bicycles and automobiles on higher speed roads (where most fatalities occur) and to reduce chances of severe injury at intersections (where most crashes occur) (*Cushing et al., 2016*). Additionally, research shows that increases in the overall number of cyclists are correlated with reductions in the number of crashes, described as a "safety in numbers" effect (*Jacobsen, 2003; Fyhri et al., 2017*). On average, women are more risk-averse than men (*Byrnes et al., 1999*), preferring greater separation from automobiles while bicycling (*Garrard, 2008*). In order to increase rates of cycling, it is imperative to cater to cyclists' safety preferences by creating infrastructure that can be comfortably used by everyone. Provision of adequate infrastructure may be a method to achieve the safety in numbers effect, as bicycle infrastructure has been shown to have an induced demand effect (*Skov-Petersen, 2017*).

In order to implement changes that are known to improve safety, and to implement them in the most effective way possible, having reliable data to support decision making is critical. Data such as safety, perceived safety, crashes, near misses, willingness to cycle, and traffic volume can all be used to inform the type and location of bicycle infrastructure in order to effectively impact safety and encourage cycling as a mode of transportation. Cycling data is an enduring barrier and this dissertation will discuss at length several cycling data sources, particularly crash data, survey data, and ultimately data from a virtual reality (VR) bicycle simulator.

As will be discussed in chapters two and three, crash and hospital data are frequently used to study cyclist safety because they are relatively accessible and can be fairly large datasets. They provide some of the most thorough and easily available cycling data, however, they have a number of limitations. Crash data is highly underreported, and reported crashes are biased towards higher injury crashes. Crash data is designed to capture motor vehicle crash information and does not capture key cyclist characteristics. Perceived safety, risk, and comfort data is another frequently used source of cyclist data because it can be used as a surrogate for measured safety, and low levels of perceived safety are a barrier to people choosing to cycle. Research methods frequently include collecting stated preference data through interviews, standalone surveys, surveys involving video clips or simulations, and intercept surveys. Research methods to collect revealed preference data include naturalistic cycling experiments, and recently, VR experiments.

Stated preference surveys are subject to hypothetical bias, where respondents tend to answer differently to hypothetical situations than they would in real world scenarios. Revealed preference experiments do not face this limitation, but have their own drawbacks. Compared to stated preference surveys, naturalistic experiments are costlier and are limited in the range of preference experiments which can be feasibly posed to a subject. Recent studies have shown that VR is an effective tool to replicate realistic environments for transportation research (*Deb et al., 2017*). VR offers a promising compromise between the limitations of stated preference surveys and field experiments, allowing for a large variety of preference experiments to occur in a controlled environment where subjects are immersed in a real world-like setting.

Due to the limitations in existing cycling data, and the potential of VR to address some of these gaps, we designed a bicycle simulator outfitted with the latest technological advancements in sensors, VR, and bicycle trainer equipment. This dissertation will discuss the design and development of the bicycle simulator, validating the simulator against real world data, and using the simulator to study perceived safety of cyclists.

1.2 RESEARCH OBJECTIVES

There are three main research objectives for this work.

I. Development of a VR bicycle simulator reflecting real-world conditions. The simulator in this study allows the participant to pedal, steer, and brake in VR, while collecting detailed physiological and sensor data, a state-of-the art achievement in this field.
II. Development of a methodology to validate the bicycle simulator by comparing participants' behavior to that of real-world cyclists. The bicycle simulator field is lacking in consistent validation methods of simulators. This research presents one.
III. Innovative methods to assess perceived cyclist safety from novel data sets, including both stated preference and sensor data. Perceived safety (or lack thereof) is a major barrier to increasing bicycle mode share. As cyclists benefit from a "safety in numbers" effect it is critical to understand specific elements that impact perceived safety.

1.3 ORGANIZATION OF THE DISSERTATION

1. The first chapter of this report covered the motivation for the dissertation work, and research objectives that will be fulfilled.
2. The second chapter of this report is a review of the relevant literature. This spans such topics as bicycle safety (both measured and perceived), technology advancements in immersive virtual environments (IVE) and head mounted displays (HMD), IVE applications for driving safety research and driving simulation, bicycle simulation development, the application of VR technology to address bicycle safety through research with simulators, and gaps in bicycle simulation research which are addressed by this dissertation.

3. The third chapter of this report covers my own previously completed work which forms the motivation for this dissertation. The previous work includes analysis of Virginia bicycle crash data, and the development, distribution and analysis of survey data. These studies led us to look at VR technology as an answer to some of the bicycle data problems.
4. The development of the VR bicycle simulator in the Omni-Reality and Cognition Lab (ORCL) comprises the fourth chapter of this dissertation. This chapter includes the justification for various technology decisions and a description of all components of the simulator.
5. Chapter five covers the validation study developed for the bicycle simulator. The validation study includes several key datasets. The first is video footage collected from a real-world corridor in Charlottesville. The second is data collected from the bicycle simulator as participants cycle through a virtual recreation of the Charlottesville corridor. The third is survey data collected from bicycle simulator experiment participants after they complete the virtual experiment.
6. Chapter six delves into the bicycle infrastructure and perceived safety experiment which serves as a model for how the simulator can be used to study various bicycle roadway conditions and cyclists' perceptions of those conditions using novel sources of data from the simulator.
7. Finally, chapter seven concludes the dissertation, discussing the key contributions of the work, limitations of the studies, and future work in this field.

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CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

The following chapter details the relevant literature for the bicycle simulator research. This section begins with an explanation of factors that impact measured and perceived bicycle safety to inform the design of the bicycle simulator experiments. These topics are followed by a discussion of the relevant technology literature, including virtual reality advancements, motor vehicle simulators, the history of bicycle simulators, and the gaps in bicycle simulation research.

2.2 FACTORS INFLUENCING MEASURED CYCLIST SAFETY

Previous studies have identified many possible factors contributing to crashes between bicycles and automobiles, including infrastructure, environmental, and temporal factors, as well as driver, vehicle, and roadway characteristics. Reynolds et al. (*2009*) reviewed 23 papers that examined the effect of transportation infrastructure on bicyclist crashes and injury, concluding that bicycle-specific facilities such as bike routes, bike lanes, and off road bike paths reduce cyclist crashes and injury. Bicycle-specific facilities are in contrast with multi-use roads where bicycles share motor vehicle lanes or travel on sidewalks. Additionally, cyclist safety was shown to improve with street lighting, paved surfaces, and low angle grades (*Reynolds et al., 2009*). In addition to transportation facility and environmental factors, human factors also contribute to bicycle and automobile crashes. Lack of attention from cyclists and automobile drivers about their surroundings, as well as unclear expectations about the behavior of other cars and bikes on the road, leads to bicycle and automobile crashes. For example, Rasanen and Summala (*1997*) conclude that the most common bicycle-car collision results when the driver looks left for oncoming vehicles when they should also be looking right for cyclists. This lack of driver expectation about where cyclists will be and how they will behave increases the occurrence of bicycle-automobile crashes.

Other studies have focused on environmental factors that specifically affect injury severity in bicycle and automobile crashes. Identifying factors that contribute to the most severe cyclist injuries can motivate policy and infrastructure changes to prevent the most debilitating of crashes. Previous studies have shown that temporal and environmental characteristics can influence injury severity. By cycling at night, the likelihood of a severe cyclist crash increases (*Eluru et al., 2008; Rodgers, 1995*). Eluru et al. (*2008*) found that riding between midnight and 6 a.m. increases the probability of a fatal accident by almost five-fold compared to daytime (6 a.m.–6 p.m.) riding. Night time riding is particularly dangerous in areas without streetlights (*Yan et al., 2011; Kim et al., 2007; Klop and Khattak, 1999*). Kim et al. (*2007*) identified cycling at night without streetlights as a crash injury risk, increasing the probability of a fatal injury by 110.9% compared to crashes occurring in daytime or in areas with streetlights. Similarly, fog leads to a reduction in visibility and has been shown to be a risk factor for increased injury severity (*Klop and Khattak, 1999*). More broadly, inclement weather has been identified as a factor in doubling the risk of a fatal cyclist injury (*Kim et al., 2007*).

Cyclist characteristics, such as age, gender, and alcohol consumption, are also risk factors for increased cyclist injury severity. Numerous studies have cited old age as a risk factor (*Yan et al., 2011; Moore et al., 2011; Eluru et al., 2008*). Kim et al. (*2007*) specifically describe cyclists over the age of 55 as a factor that could double the risk of a fatality. Similarly, Rodgers (*1995*) concludes that cyclists older than 44 are at a greater risk for a fatality and Eluru et al. (*2008*) found that cyclists over age 60 are more than four times more likely to be fatally injured compared to cyclists younger than 60. Rodgers (*1995*) also found that males have a five times greater risk of being killed in a bike crash compared to females, when adjusted for exposure. Alcohol consumption has also been shown to increase severe injuries. Sethi et al. (*2016*) found that alcohol use by urban cyclists was inversely correlated with helmet use and associated with more severe injuries and greater mortalities. Andersson and Bunketorp (*2002*) found that intoxicated cyclists less often wore helmets and were at a greater risk of head and face injuries. Specifically, Moore et al. (*2011*) found that when the automobile driver was under the influence of alcohol, the likelihood of a severe injury increased by 82.2% if the crash occurred at an intersection and 150.1% at a non-intersection location. Kim et al. (*2007*) also found the probability of a fatal injury to more than double if either the cyclist or the driver in a crash were intoxicated.

Automobile characteristics such as speed of the automobile, type of automobile, and angle at which the automobile collided with the bicycle have also been shown to affect injury severity. In several studies, high vehicle speed at the time of collision increased likelihood of a severe injury. The exact speed which constitutes a high speed is not consistent in all studies, with most studies simply concluding higher speeds lead to more dangerous crashes (*Eluru et al., 2008; Yan et al., 2011; Moore et al., 2011*). Kim et al. (*2007*) specifically identify speeds above 30 mph to double the probability for a fatality, and that speeds above 50 mph increase the risk of fatality by 16 fold. Eluru et al. (*2008*) found that speeds above 50 mph increase fatality risks by 470.81%. Additionally, if the vehicle involved in the accident is a heavy-duty vehicle, injury severity risk also increases (*Yan et al., 2011; Kim et al., 2007; Moore et al., 2011*). Kim et al. (*2007*) find that in bicycle collisions with heavy trucks, the probability of a fatality increases by 390.9% and the probability of an incapacitating injury increase by 101.8%. Furthermore, head-on (*Yan et al., 2011; Kim et al., 2007)* and angle collisions (*Yan et al., 2011; Moore et al., 2011*) were shown to increase injury severity. Kim et al. (*2007*) found that head-on collisions double the probability of a fatal injury.

Lastly, roadway characteristics have been shown to affect injury severity levels. Kim et al. (*2007*) found that divided roads increase non-incapacitating injuries by 13.5%. Yan et al. (*2011*) found that fewer cyclists rode against traffic when there was a median, which was previously hypothesized by Kim et al. (*2007*) as a reason for reduced injury severity on divided roads. Klop and Khattak (*1999*) discuss grades on straight and curved roads as being detrimental to bike safety. Additionally, Moore et al., (*2011*) found horizontal curves with grades in intersections and horizontal and vertical curves at non-intersection locations to increase injury severity. Eluru et al., (*2008*) also found that crashes at signalized intersections were less severe than at other locations, reducing the probability of a fatal crash by almost 90%.

Methods used to study factors impacting cyclist safety are often derived from just a couple types of safety data. The most commonly used data in the studies described above is crash data. Crash data is frequently used for bicycle safety research due to its ease of access and the broad number of crash characteristics that are captured in police reports. In addition to crash data, injury data, typically derived from hospital records, is commonly used to study bicycle safety. Other data sources include fatality data, in the US this comes from the Fatality Analysis Reporting System, and in some cases, multiple sources are combined to achieve a more complete dataset, for example telephone interviews have been used to add survey data to hospital record data. Due to the potential to acquire a fairly large dataset, modelling techniques such as multivariable analysis, multinomial logit model, ordered probit model, mixed logit model, and mixed generalized ordered response logit model have been used to analyze crash data and hospital injury data. These datasets remain useful tools for studying bicycle safety, despite their many drawbacks. Crash data is highly underreported with a strong bias toward severe injury crashes, and is designed to record motor vehicle crashes, resulting in a lack of information about key characteristics relevant to cyclist safety. The limitations of crash datasets will be described in depth in Chapter Three.

2.3 FACTORS INFLUENCING CYCLISTS' PERCEIVED SAFETY, COMFORT, AND STRESS

Perceived safety is an important measure because it can be a barrier to the uptake of cycling and because it has been shown to be an indicator of actual safety (*Manaugh et al., 2017; Manton et al., 2016*). Improving the safety of the cycling environment is critical to reducing fatalities and injuries and increasing engagement with micromobility to reduce auto dependency. In reviewing the past work on cyclist perceived safety literature, several metrics are frequently used to quantify the cyclist experience including: measured levels of perceived safety, comfort, and stress, as well as level of traffic stress (LTS) and bicycle level of service

(BLOS). The literature shows that cyclists' feelings of perceived safety, risk, or comfort are dependent upon numerous factors relating to roadway infrastructure, the traffic environment, and cyclists' own characteristics and experiences.

For example, some characteristics associated with decreased perception of safety include: insufficient space allocated to the cyclist; lack of a paved shoulder; high traffic speed; high traffic flow; the presence of heavy trucks; sand/gravel/or vegetation pavement types; presence of ditches; intersections; curves; hills; the number of automobile lanes; curbside parking; combined pedestrian and cyclist paths; reckless or careless driver attitudes; and the use of helmets, high visibility clothing, lights, and reflectors (*Noël et al., 2003, Chataway et al., 2014 Lawson et al., 2013*). Alternatively, literature showed that parents perceive presence of a bicycle lane as safer than lowering speed limits (*Nevelsteen et al., 2012*), and bicycle lanes were associated with increased feelings of safety (*Chataway et al., 2014*).

Perceived risk was found to reduce with the presence of bicycle facilities, particularly off-road facilities or facilities adjacent to the road (*Parkin et al., 2007*). Bicycle facilities at roundabouts and intersections were found in one study to have no significant impact on perceived risk (*Parkin et al., 2007*) and in another study bicycle facilities at roundabouts improved feelings of safety (*Møller and Hels, 2008*).

While the research on perceived safety and risk covers a variety of roadway, traffic, and cyclist characteristics, the literature on perceived comfort appears to converge on the conclusion that cyclists prefer greater separation between themselves and motor vehicles. Separated paths were found to significantly increase cyclist comfort (*Blanc and Figliozzi, 2016*), physical barriers increased comfort more than pavement markings (*Monsere et al., 2014; McNeil et al., 2015*) and pavement markings increased comfort more than signs (*Abadi and Hurwitz, 2018*). Other factors that decreased comfort included interactions with other road users (*Werneke et al., 2015*), poorly maintained infrastructure (*Werneke et al., 2015*), automobile traffic (*Blanc and Figliozzi, 2016),* heavy vehicles (*Blanc and Figliozzi, 2016; Abadi and Hurwitz, 2018*) insufficient passing distance (*Apasnore et al., 2017*), traffic density (*Apasnore et al., 2017*), uphill roads (*Oh et al., 2017*), and poor surface conditions (*Oh et al., 2017*).

There are many similarities among the elements which affect bicyclist perception of safety, risk, and comfort, and those associated with LTS (traffic volume, speed, lane width, level of separation, motor vehicle traffic, parking lane, street width, intersection crossing difficulty) (*Sorton and Walsh, 1994; Mekuria et al., 2012*) and BLOS (traffic volume, passing maneuvers, bike lane presence, conflicts, speed differential, motor vehicles, maintenance, network, outside lane width, bike lane width, shoulder width, on street parking, volume, speed, heavy vehicles, pavement, curb presence, and number of lanes) (*Botma, 1995; Dixon, 1996; Highway Capacity Manual, 2010*). Nearly all elements used in the literature to quantify traffic stress and BLOS have been found in some form to impact perceived safety, risk, or comfort.

The literature also indicates that new methods to measure perceived safety, risk, and comfort are needed. Technology has advanced this field of study since it began in the 1990s. Research methods across these topics are dominated by the use of stated preference surveys and (less frequently) interviews, beginning with standalone surveys and later evolving to include supplementation of video clips, simulations, and real-world environments (by means of intercept surveys). Stated preference surveys, though less costly to deploy than field experiments, can elicit different responses based on how the information is presented, what questions are asked, and how responses are formatted. In this body of literature, one can observe a trend towards more sophisticated and controlled ways to present information (via supplementation of video clips and simulations) so that it is less open to interpretation. Stated preference responses are also susceptible to hypothetical bias, where respondents tend to answer differently to hypothetical situations than they would in real world scenarios. Only a handful of studies in the large body of literature reviewed here gathered revealed preference data via smartphone apps or naturalistic bicycling experiments. While free of hypothetical bias, revealed preference experiments have their own limitations. First, such field experiments are costly to conduct. Second, due to the nature of naturalistic experiments, a narrower range of preference experiments can be posed to the subject (as these combinations of roadway, traffic, and bicyclist characteristics must be replicated in the real world setting), as compared to the wide range of hypothetical choice experiments that can be posed in a stated preference survey. Recent studies have shown that VR is an effective tool to replicate realistic environments for transportation research (*Deb et al., 2017*). VR offers a promising compromise between the limitations of stated preference surveys and field experiments, allowing for a large variety of preference experiments to occur in a controlled environment where subjects are immersed in a real world-like setting. One study (*Nazemi et al., 2021*) has deployed VR technology to assess perceived safety of cyclists. Recent literature demonstrates how technology has allowed researchers to explore new methods by combining videos, instrumented bicycles, smartphone apps, and surveys to enhance older methods. The future of research in perceived safety, comfort, and risk in bicycling will likely focus on using technology to recreate more realistic cycling experiences in order to test impacts of infrastructure and traffic characteristics.

2.4 BICYCLE SIMULATION

Physical simulation is a promising approach to assessing cyclist behavior and comfort in different traffic environments. Simulation minimizes the hypothetical bias of stated preference surveys and offers a controlled, low-risk environment that real-world revealed preference experiments cannot guarantee. Driving simulation is a well-established tool for studying motor vehicles and has been used to study such topics as distracted driving (*Papantoniou et al., 2017*), drowsy driving (*Soares et al., 2020*), the impact of drugs such as opioids and alcohol on driving skills (*Ferreira et al., 2018; Irwin et al., 2017*), the impacts of Alzheimer's disease, traumatic brain injury, and ADHD (*Hird et al., 2016; Imhoff et al., 2016; Jerome et al., 2006)* on driving, and to assess impacts of roadway geometry on driver behavior (*Bobermin, et al., 2019).* Notably, a review of driving simulator validation studies shows that only about half of the studies reviewed achieved absolute or relative validity, without a clear relationship to fidelity, and suggests guidelines for consistency in future work (*Wynne, et al., 2019*). The breadth of these topics shows that driving simulators have been applied extensively to motor vehicle safety research, yet in some cases lack validation. The driving simulation field is considerably larger than that of the bicycle simulation field, and it provides an example of the many directions bicycle simulation research could take, particularly as technology advances, and virtual reality is incorporated into simulators. The growing body of work using bicycle simulators to study behaviors and safety of non-motorized travelers will be discussed in the following section.

As much as bicycle simulators have evolved in the past few decades, many of the key components remain the same, including physical engagement through pedaling, steering, braking, and visual representation through a screen or head mounted display (HMD). Some simulators have included additional elements such as tilting, pedal resistance, rear wheel friction, handlebar resistance/feedback, and sound ((*Van Veen et al., 1998; Kwon et al., 2001; Chihak et al., 2010; Shoman and Imine, 2020; Kearney et al., 2006*)). These additional elements are intended to enhance the realism of the simulator by including more components of real-world cycling experiences. Visualization is one of the core elements of a bicycle simulator, and one that has benefited significantly from advances in technology. Most early simulators relied solely on screens for visualization as opposed to HMDs (*Van Veen et al., 1998; Shoman and Imine, 2020; Kearney et al., 2006; Plumert et al., 2004; Plumert et al., 2011; Stevens et al., 2013*). In the past five years, with the advent of commercially available HMDs such as the Oculus Rift and the HTC Vive, simulation labs have begun using virtual reality (VR) technology more frequently to display the virtual environment (*(Maheshwari et al., 2016; O'Hern et al., 2017; Xu et al., 2017; Brown et al., 2017; Kwigizile et al., 2017; Lee et al., 2017; Keler et al., 2018; Sun and Qing, 2018; Nazemi et al., 2018)*). HMDs are capable of providing a more immersive visual experience than viewing a screen. The headset physically covers the eyes, blocking out exterior light and when equipped with headphones, they also block out sounds, allowing the user to focus more completely on the visualization inside the headset. The intention is to increase immersion and realism, and for research purposes, increase the realism of user behavior. Birenboim et al. used SP experiments within an immersive virtual environment (IVE) for a bicycle simulator to determine that IVEs seemingly generate a greater sense of presence compared to viewing still images (*Birenboim et al., 2019*). Similarly, Farooq et al. (*Farooq et al., 2019*) used a Virtual Immersive Reality Environment (VIRE) for pedestrian research and compared results with those from visual aids and text-only approaches. The authors found more consistent results with the VIRE. These results underscore the benefits of immersive VR technology compared to other methods for SP research. In bicycle simulators, however, the use of screens for display persists in some simulators due to the limitations of HMDs. HMDs are known to cause simulator sickness in some users. Additionally, for many people, HMDs are still an unfamiliar technology. There is a learning curve associated with the familiarization process that is necessary prior to the experiment. Screens do not present these same barriers; but they cannot achieve the immersiveness that HMDs excel at.

This body of work is summarized in *Table 1*, giving details about technology, immersion, data, and analysis. Simulators are capable of addressing several problems practitioners and researchers face in improving bicycle and pedestrian safety, including a better understanding of user comfort within different roadway designs. Recent advancements in VR technology have created opportunities for transportation researchers to develop frameworks to test its validity in transportation simulators. The potential benefits of using virtual, augmented, and mixed reality technologies by the transportation community, particularly for bicycle research, are significant: enhanced educational safety programs, informed public feedback on proposed transportation projects, understanding the perceived safety and comfort of transportation facilities. Moreover, virtual environments are easily modifiable and highly controlled, unlike real world conditions, which can vary greatly (e.g., weather, vehicle volumes, and lighting).

Gaps in the current research include studies involving multiple subjects (performing the same or different roles i.e. pedestrian, cyclist, driver, etc.) in the same virtual environment simultaneously, augmented reality, subjects with disabilities in risky scenarios, and utilizing virtual environments as a tool for demonstration and education in public forums. Additionally, there is a lack of comparison studies of the effectiveness of screens compared to HMDs among bicycle simulator research. It is difficult to draw conclusions relating to technology effectiveness between a simulator using screens and another using HMDs because validation methods are not consistent. In order to assert one technology as preferable to other visualization methods, or to be able to compare other results between simulators, validation methods should be standardized.

Some validation studies do exist. O'Hern et al. (*O'Hern et al., 2017*) combined an HMD with an instrumented bicycle that was capable of tracking head movements, speed, steering, and braking. The researchers conducted an experiment with 26 participants comparing on-road and in-simulator performance to validate elements of the simulator. The researchers were able to establish absolute validity for bicycle lane position, deviation in bicycle lane position, and average passing distance of the bicycle from parked cars as well as relative validity for bicycling speed and speed reduction when approaching an intersection between the on-road and in-simulator cyclists. Additionally, Nazemi et al. (*2018*) developed an instrumented stationary bicycle using an HMD for use in validating perception of speed and space in a bicycle simulator. Tests have involved participants on a stationary bicycle wearing an HMD and watching cars pass them on the roadway. Participants were asked about their perceptions of speed and space of the vehicles through a series of survey questions, to better understand the validity and limitations of human perception in VR. The authors found that participants could differentiate speed differences of passing cars of 20 km/hr and 30 km/hr easily, but had difficulty perceiving when cars speeds changed by 10 km/hr. Additionally, participants could perceive when bike lanes changed by ±1.2 m, ±0.9 m, and ±0.6 m in width but had difficulty perceiving changes of ±0.3 m and 0.0 m. O'Hern et al., and Nazemi et al., present different approaches to validation, the former using real-world instrumented bicyclists and the latter examining the capabilities of human perception within a VR environment. However, there are still very few studies which have validated simulators with real-world conditions. In driving simulation research, these validation studies are more common, and there is a need for better methods in cycling simulation research. In this dissertation a different method of validation is trialed, using video collection to gather a dataset about real-world bicyclists, a bicycle simulator to gather data about bicyclists in VR environments, and survey data to gather perceptions of realism. This work will be discussed at length in Chapter Five.

Report Information			Visual Technology			Level of Immersion					Data Reported				
						Agency of Movement									
Year	Author	Laboratory	Single Screen	Multiscreen or CAVE	HMD	*Stationary*	*Dummy*	*Real Time*	Sound	Haptic Feedback	Kinematic	Movement	Eye Tracking	Physiological Feedback	Stated Preference
1998	Van Veen et al.	Max-Planck-Institute for Biological Cybernetics	X (Curved Single Screen)		Virtual Research V8			X		Pedal Resistance	Speed, Steering, Tilt				
2001	Kwon et al.	KAIST Bicycle Simulator	X		X			X		Handlebar and Pedal Resistance	Six Degree of Freedom Motion, Tilt, Steering, Speed, Braking	x			
2004	Plumert et al.	Hank Virtual Environments Lab		X				X		-	Speed, steering, braking				
2006	Kearney et al.	Hank Virtual Environments Lab		X				X	X	-	Speed, steering				
2010	Chihak et al.	Hank Virtual Environments Lab		X				X		Rear wheel friction	Speed, steering, braking				
2011	Plumert et al.	Hank Virtual Environments Lab		X				X	X	Rear wheel friction	Speed, steering, braking	X			
2013	Grechkin et al.	Hank Virtual Environments Lab		X				X	X	Rear wheel friction	Speed, steering, braking				X
2013	Stevens et al.	Hank Virtual Environments Lab		X				X	X	-	Speed, steering, braking				X
2014	Chihak et al.	Hank Virtual Environments Lab		X				X		Rear wheel friction	Speed, steering, braking				
2015	Nikolas et al.	Hank Virtual Environments Lab		X				X	X	Rear wheel friction	Speed, steering, braking				X
2016	Maheshwari et al.	Future Cities Laboratory			HTC Vive and Oculus Rift		X			-					X
2017	O'Hern et al.	Monash University Accident Research Centre			X		X			-	Speed, steering, braking	X			X
2017	Xu et al.	Intelligent Human Machine Systems Lab, Northeastern University			Oculus Rift DK2	X				-	Speed, braking				X
2017	Brown et al.	ZouSim, University of Missouri		X	X			X		-	Speed, steering, braking				X
2017	Kwigizile et al.	Transportation Research Center for Livable Communities Laboratory			Oculus Rift			X		Wheel Resistance	Speed, steering			EEG	X
2017	Lee et al.	Delft University of Technology			Oculus Rift			X		-	X				
2017	Stroh	University of Iowa		X				X		-	Velocity, steering, inertia				
2018	Keler et al.	TUM-VT Technical University Munich	X		X			X		-	Speed, steering				
2018	Sun and Qing	ZouSim, University of Missouri		X	X			X		Wheel Resistance	Speed, steering, braking				
2018	Nazemi et al.	Future Cities Laboratory			X		X			-					X
2018	Powell et al.	Hank Virtual Environments Lab		X				X		Pedal resistance	Speed, steering, braking				
2019	Abadi et al.	Oregon State University	X					X	X		Speed, braking				
2020	Shoman et al.	IFSTTAR		X				X		Rear wheel Force Feedback, Handlebar Force Feedback, Aerodynamic Resistance	Pedals, Handlebars, Braking, Tilt, Gears				X
2021	UVA	ORCL			HTC Vive			X	X	Rear wheel resistance, Wind Resistance	Speed, braking, steering	X	X	Smartwatch	-
2021	Nazemi et al.	Future Cities Laboratory			HTC Vive			X		Rear wheel resistance	Speed, Braking, Tilt	X			X
2021	Shoman et al.	Perceptions, Interactions, Behaviors and Simulations Lab, Gustave Eiffel University		X				X		Handlebar Force Feedback, Wind Resistance, Rear wheel adhesion, Vibration Actuators	Pedals, Handlebars, Braking, Tilt, Gears				X
2021	Cobb et al.	Oregon State University	X					X	X		Speed, braking	X		Galvanic Skin Response	X
2021	Keler et al.	TUM-VT		X				X			Speed, steering	X			

Table 1. Bicycle Simulator Overview

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CHAPTER THREE: PREVIOUS WORK

3.1 INTRODUCTION

In order to explore basic questions about cyclist safety we need data. For bicycle research, the lack of comprehensive data sources presents a significant barrier. As a graduate student at the University of Virginia, my research has spanned many facets of bicycle safety, and each time we have refocused on a new research path, high quality data has been at the crux of the decision, ultimately leading to the main focus of this dissertation, the development of an immersive virtual reality bicycle simulator. The first research project that I worked on at UVA involved an analysis of Virginia police reported crash data. The second and third major projects both involved the design and dissemination of surveys. One survey captured crash histories and attitudes of Virginia bicyclists, the other was a partnership with the Virginia Transportation Research Council where we asked practitioners in every locality (town, city, planning district commission, VDOT planning district) in Virginia about their experience implementing bicycle infrastructure. The strengths and limitations of each of these data sources led us to explore the use of virtual reality (VR) simulation and video footage to study cyclists. The following chapter discusses these previous studies, as well as how they motivated specific components of this dissertation research.

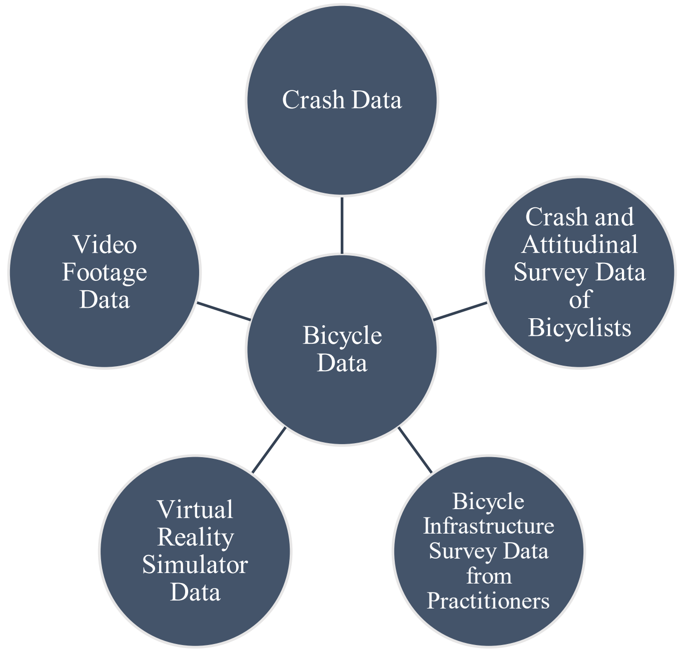

Figure 1. Variety of bicycle data utilized in this research.

3.2 THE EFFECT OF CRASH CHARACTERISTICS ON CYCLIST INJURIES: AN ANALYSIS OF VIRGINIA AUTOMOBILE-BICYCLE CRASH DATA

For the full study description see *Robartes and Chen, 2017*.

To study cyclist safety across the Commonwealth of Virginia, crash data was chosen because it is commonly used by transportation engineers to study safety for motor vehicles. It is easily accessible and includes standardized variables about each crash making it invaluable for understanding safety problems. However, as will be evidenced by this work, it has limitations when used for cyclist research. Crash data is collected through police reports which are written up in the event of a crash. They may be single vehicle crashes, multiple vehicle crashes, or involve other transportation modes (i.e. cyclists or pedestrians). Each state has different requirements for the severity or property damage level of an accident that necessitates the writing of a police report. In the Commonwealth of Virginia, any motor vehicle accident involving injury or death of a person or property damage estimated to be at least $1500 (*NHTSA, 2014*) necessitates a police report.

For this study, data came from Virginia police crash reports collected between 2010 and 2014 across the entire state. The Virginia Department of Motor Vehicles (VA DMV) provided information for 3679 reported crashes involving a bicyclist. The data include characteristics about the crash, roadway, environment, vehicles (bicycles and automobiles), and drivers (cyclists and automobile drivers). One element of interest which warrants further discussion is the injury severity variable of the cyclist involved in the crash. The Virginia Police Crash Reporting Manual categorizes injury outcomes as fatal, severe injury, minor/possible injury, no apparent injury, and no injury. The cyclist injury category is determined at the discretion of the police officer (given provided manual guidelines) at the scene of the crash. Fatalities include all injuries that result in death within 30 days of the accident. Severe injuries include severe lacerations, broken or distorted limbs, crush injuries, significant burns, unconsciousness or paralysis. Minor or possible injuries include visible injuries such as bruises, abrasions, swelling or limping. No apparent injury is cited when there is no visible injury but the person complains of pain or becomes briefly unconscious. No injury is recorded when by the officer's best judgement, no injury has occurred (*NHTSA, 2014).* This method of injury severity collection is open to subjectivity on the part of the police officer.

While all the crashes in the VA DMV dataset involve cyclists, they do not all involve the same number of bicycles and automobiles. For the purpose of this research (due to limited sample size of other crash types), only crashes between one automobile and one bicycle are included. 3545 (96.4%) of the original VA DMV dataset are single automobile and bike crashes. The removed crash observations include single bicycle crashes (where no automobile was identified), multiple bike crashes, and crashes involving multiple automobiles. The purpose of this limitation is to focus directly on the dynamic between a single automobile and a single bicycle without confounding the physics and interpretation of the crash.

Useful summary statistics from the Virginia crash dataset reveal characteristics surrounding gender, speed, roadway geometry, and environmental characteristics. Males comprise 77% of bicyclists, compared to 18% of females. Distribution of gender among automobile drivers is more evenly split with males (54%) still topping females (45%) in total crashes. In fatal crashes, the male to female ratio of cyclists is 14 to 3 which is similar to the total gender ratio. However, for automobile drivers the male to female ratio in fatal crashes is 15 to 5, showing males overrepresented as drivers in fatal crashes. Other crash statistics involve vehicle, roadway, and environmental characteristics. Passenger cars are the most common type of vehicle in automobile-bicycle crashes (61%), second are SUVs, light duty trucks, and vans, which together account for 35%. Vehicle speed before crash is a variable that is prone to estimation error as it is determined by the police officer after examining the physical evidence at the scene and interviewing the automobile driver. However, speed is an important factor in defining the dynamics of the crash. Roadway characteristics show that 32% of crashes occurred at non-intersection locations and 60% occurred at intersections with three or more approaches. Roadway characteristics also show that most crashes occur on concrete or asphalt roads in dry conditions, on straight and level roads. Environmental characteristics show that the majority of crashes (79%) occurred during daylight hours and 6% of crashes occurred when the weather involved precipitation (fog, mist, rain, or snow).

Other conclusions involve key metrics missing from the police reported crash data which limit the use of it for cyclist analysis. Police reported crash datasets are designed to record motor vehicle crashes and resultantly fail to provide a complete picture of cyclist crashes. For example, useful data such as the bicycle infrastructure at the crash site (bike lane, shared road, no infrastructure) would help to understand how bike infrastructure impacts safety. Additionally, equipment like lights and reflectors are lacking in crash databases. Virginia requires a white light on the front of a bicycle and a red reflector (red light when the speed limit is over 35 mph) on the back of the bicycle after sunset (*Va. Code Ann. § 46.2-1015*). Inclusion of visibility features would be useful for studying cyclist safety. Furthermore, the helmet variable in the dataset was only partially usable due to coding errors. Helmets are also a critical safety feature and recording data about usage would be meaningful for bicycle safety research. Finally, and most importantly, bicycle crashes are highly underreported in police reported crash datasets, particularly for minor crashes (as they fail to meet the reporting threshold).

An ordered probit model was used to examine single bicycle-single vehicle crashes from Virginia police crash report data and how various crash characteristics impact the probability of cyclist fatalities and injuries. In this study, the response variable is the injury severity of the bicyclist in the crash, represented by the following five categories: fatal (0), severe injury (1), minor/possible injury (2), no apparent injury (3), and no injury (4). The crash, roadway, environment, vehicles (bikes and automobiles), and drivers (cyclists and automobile drivers) characteristics are the independent variables in the model. Two of the most impactful model results are the influence of intoxicated cyclists and drivers on injury severity outcomes. The results show that cycling while inebriated doubles the probability of severe injury for the cyclist and increases the probability of a fatality by 36.7%. This study also found that drunk drivers increase the fatality risk for cyclists more than any other factor studied; driver intoxication increases the probability of a cyclist fatality six fold and doubles the risk of a severe injury. Additionally, bicycle and automobile speeds, obscured automobile driver vision, specific vehicle body types (SUV, truck, and van), vertical roadway grades and horizontal curves elevate the probability of more severe bicyclist injuries. Model results encourage consideration of methods to reduce the impact of biking and driving while intoxicated such as analysis of bicycling under the influence laws, education of drunk driving impacts on bicyclists, and separation of vehicles and bicycles on the road. Additionally, the results encourage consideration of methods to improve visibility of cyclists and expectation of their presence on the road.

As a result of the limitations of crash data summarized above (no bicycle infrastructure data, minimal safety equipment data, and underreporting of data) we initiated a project to collect data which would asses those limitations. We chose to move forward with a survey project, canvassing cyclists all over the state of Virginia, to collect the kind of data lacking in police reports.

3.3 CRASH HISTORIES, SAFETY PERCEPTIONS, AND ATTITUDES AMONG VIRGINIA BICYCLISTS

For the full study description see *Robartes and Chen, 2018*.

A Virginia statewide survey was designed to capture bicycle crash histories as well as personal cyclist attitudes and perceptions of safety. Survey distribution relied on solicitations to bicycle organizations, clubs, and advocacy groups in the spring of 2017. Additionally, with the goal of capturing responses from casual or non-riders, the survey was distributed locally at an event hosted during Bike Month in Charlottesville, Virginia. The distribution of the survey did not reflect a random sampling of the population. However, with limited distribution resources and low bicycling rates among the general population, this method ensured the survey would reach the bicycling community in Virginia. Dill et al. (*2016*) analyzed this tendency of bicycle surveys to solicit responses specifically from established bike groups to determine the effect on the results. Dill et al. (*2016*) found that this sampling method does yield statistically different responses to identical questions posed to a general random population. However, they found that in many cases, the differences are small and do not lead to different conclusions. A total of 686 survey responses were recorded, including people who began the survey but did not complete it. Of the 686 responses, 459 people (66.9%) completed the survey.

The survey included Likert scale questions on cyclists' use of safety equipment, perceptions of driver behavior, behavior as a driver, perceptions of safety while cycling, and knowledge of local cycling laws. A few of the interesting results will be discussed here (for a full discussion of the survey questions see *Robartes and Chen, 2018*). Summary statistics of these questions show very high rates of bicycle safety equipment usage. The majority of respondents state that they always wear a helmet (78%) and always use lights on their bikes at night (69%). Additionally, 31% of cyclists always wear reflective clothing at night and 64% at least sometimes do. Finally, a majority of the sample report using lights on their bike during the day, with 19% recording always, 13% usually, and 21% sometimes. A multinomial logit (MNL) model *(Greene, 2008)* was employed to determine characteristics that influence a cyclist's decision to always, usually, sometimes, rarely, or never wear a helmet. Model results indicate that as age increases, respondents are more likely to wear a helmet (with a one unit increase in age, respondent is 1.19 and 1.15 times more likely to always or usually wear a helmet rather than never, respectively). Older cyclists are associated with a greater risk of injury in the event of a crash *(Yan et al., 2011; Moore et al., 2011; Eluru et al., 2008; Kim et al., 2007),* thus the tendency for older cyclists to wear helmets more frequently is a positive one for safety.

When asked about how often the respondent is passed by an automobile at least 3 feet to the left, only 1% of respondents said always, 44% said usually and 40% said sometimes. Similarly, when asked if automobile drivers pass them too closely, the majority of respondents (59%) said sometimes. These statistics reveal that cyclists regularly feel that automobiles are passing them without giving the 3 feet passing space required by the Code of Virginia (*Va. Code Ann. § 46.2-839, 2014*). This may be because the driver does not know the law, does not want to comply, is giving 3 feet yet the cyclist still feels the automobile is too close, or because prior to 2014, only 2 feet of passing space was required. Regardless, a high percentage of respondents report that cars do not pass them with at least three feet of space, which leads to discomfort for these cyclists and may ultimately influence the decision to ride. Recent changes to Virginia state law aim to address insufficient adherence to the three foot passing law. Two new laws went into effect on July 1, 2021. The first requires that motor vehicles change lanes to pass a cyclist if there is not sufficient room to pass while maintaining 3 feet of space (*Va. Code Ann. § 46.2-839, 2021*). This applies even if it requires the motor vehicle to cross a solid yellow line. A second, complementary law allows cyclists to ride two abreast in a motor vehicle lane at all times, even while a motor vehicle attempts to pass them (*Va. Code Ann. § 46.2-905, 2021).* Previously, cyclists riding side-by-side were required to conform to single-file during a passing event. The new law encourages drivers to fully change lanes to complete the passing event. Together, these laws aim to make passing events safer for cyclists by requiring changing lanes to pass a cyclist to achieve at least 3 feet of passing space, and legalizing cycling two-abreast in a driving lane (encouraging lane changes for passing).

Additionally, a primary goal for this survey was to capture information about respondents' bicycle crash history. Survey respondents recorded detailed information for up to five crashes from the past ten years. Questions were asked about the injury severity of the crash, other vehicles involved in the crash, where the crash occurred (on what type of road and with what bike infrastructure), at what time of day, in what weather, if the cyclist/driver were under the influence of alcohol, and what safety equipment the cyclist was using. When asking about injury severity (serious injury, minor injury, no apparent injury, no injury), descriptions consistent with those used in the Virginia police crash report manual were used. The crash history results notably show very high levels of under-reporting of bicycle crashes, with only 44 (12%) of the 412 crashes recorded in this survey reported to police. This puts into perspective our previous research on crash data, and we can recognize that it only analyzed a small sample of bicycle crashes, and no near-miss data. Additionally, the reported crashes in the survey show that suburban and urban roads with designated bike lanes had more favorable injury severity profiles, with lower percentages of severe and minor injury crashes compared to similar roads with a shared bike/automobile lane or no designated bike infrastructure. This indicates that designated space for bikes on the road in the form of a bike lane, may provide a safer cycling environment, and this should be considered when designing roads.

From our own survey work described above, and other literature, it can be understood that designated space for cyclists on the road is correlated with increased perceived and measured safety of cyclists. However, despite known safety outcomes, it is not always easy to successfully implement bicycle infrastructure on a roadway. For example, outdated policy can inadvertently result in barriers to implementing bicycle infrastructure. A former policy in Virginia that tied roadway maintenance funding to motor-vehicle lane-miles resulted in decreased maintenance funding for localities that converted motor-vehicle lanes to bicycle lanes through roadway reconfigurations such as road diets (e.g., a 4-lane undivided roadway is converted into a road with one lane in each direction, a two-way left turn lane, and bicycle lanes, with no change in pavement width) (*Va. Code Ann. § 33.2-319*). To better understand all kinds of barriers that exist in implementing bicycle infrastructure, a second survey study was conducted.

3.4 ASSESSMENT OF LOCAL, STATE, AND FEDERAL BARRIERS TO IMPLEMENTING BICYCLE INFRASTRUCTURE: A VIRGINIA CASE STUDY

For the full study description see *Robartes et al., 2021*

Using Virginia as a case study, this research deployed a two-stage survey to assess policy, culture, and any other factors that may be discovered to hinder the implementation of bicycle infrastructure. The two-stage survey process included a preliminary survey and a detailed survey. The surveys were distributed to a comprehensive list of transportation planners, engineers, and administrators at all levels of government (town, city, county, regional, and state) within Virginia. All surveys were administered through email. In total, 236 individuals were contacted and 94 responses were received for the preliminary survey, representing a 40% response rate. The preliminary survey results provide an overall picture of bicycle infrastructure development in Virginia and highlight key opportunities for improving implementation.

At the end of the preliminary survey, respondents were asked to indicate whether or not they would be interested in sharing their experiences in bicycle infrastructure implementation in greater detail. A link to the study's detailed survey (also developed in Qualtrics) was then emailed to the subgroup of respondents who selected "Yes". The detailed survey asked respondents to briefly describe projects that received a great deal of support or a notable amount of opposition as well as the nature of any barriers that had been faced. Participants were also asked about their level of experience regarding various bicycle infrastructure development stages, including needs assessment, planning, public outreach, funding and construction, and operations management. The second-stage survey was sent to the 67 people who had expressed interest in sharing more details when they completed the preliminary survey (27 of the preliminary survey respondents did not want to complete the second-stage version), and 23 (34%) of those 67 recipients completed the detailed survey. The second stage's focus was to uncover experiences with specific bicycle infrastructure projects rather than bicycle infrastructure implementation in general.

Some key results include that much of Virginia is actively working towards implementing new bicycle infrastructure, but there are some localities that would benefit from designated staff as well as from the development of guiding documents such as bicycle plans. Furthermore, as the success of interventions are often dependent on acceptance by the community, many localities should consider incorporating more methods of public participation in bicycle infrastructure decisions; multiple survey respondents stated that there was no established method for residents to suggest new bicycle infrastructure, with many also citing public opposition as a primary barrier to bicycle infrastructure implementation.

Respondents reported public opposition, funding (often at the expense of motorized roadway projects) and right-of-way acquisition (related to geometric constraints of current infrastructure) as primary barriers which impeded the development of new infrastructure. These major barriers were followed closely by barriers concerning specific state DOT policies and more generally, insufficient bicycle planning. Other less commonly mentioned barriers included concerns about traffic impacts (particularly loss of on-street parking and impacts on motor vehicle traffic flow) and difficulties in managing grades/topography that were not conducive to bicycling. Working in areas with land use patterns that are not ideal for utilitarian biking (sprawl, suburban, or rural areas) is also a barrier that was reported. Public opposition, the top reported barrier to getting bicycle infrastructure built, is difficult to combat but support for nonmotorized roadway projects is critical to alter auto-centric culture in the United States.

3.5 IMPLICATIONS FOR VR BICYCLE SIMULATOR RESEARCH

Each of the above projects has helped to shape the next phase of research, by exploring existing data sources and understanding their advantages and limitations. Working with Virginia police reported crash data primarily revealed that the dataset is missing key characteristics that are critical to understanding cyclist safety, including bicycle infrastructure at the crash location (sharrows, bike lane, protected bike lane, etc.), cyclist safety equipment (reflectors, lights, reflective clothing), and comprehensive helmet data. Beyond missing characteristics, simply the lack of crashes in this dataset and the skew the towards fatal and severe injury crashes is a limitation.

As discussed, the limitations of the crash data led to the development of a crash history and cycling attitude survey which was distributed to Virginia cyclists. This survey asked all participants to record their own bicycling crash histories in a more detailed manner than in the police reported crash database. The previously mentioned missing characteristics (bicycle infrastructure and safety equipment) were included, along with other characteristics such as time of day and weather. Key conclusions from this survey work including better injury profiles for crashes that occurred on roads with bicycle infrastructure, led to additional survey work, this time targeting statewide decision makers.

The survey, "Assessment of local, state, and federal barriers to implementing bicycle infrastructure" found that many barriers to building bicycle infrastructure exist in the state of Virginia. The most frequently cited barriers however, were the lack of funding, public opposition, and right of way roadway constraints.

After completing the previously described projects, we wanted to find a way to collect unique data for cyclists by exploring the possibility of using VR simulation to further understand cyclists' perceived comfort and safety in different roadway environments. Simulation could address some of the previously cited barriers. For example, a possible use for VR is to improve public involvement with transportation planning projects. Having people use VR to immerse themselves in a proposed roadway design would allow them to understand the benefits.

As described in the previous chapter, VR presents a unique opportunity to improve upon or accompany standard survey methods and crash datasets to study safety. Based on the described work with common bicyclist data sources for safety, behavior, and attitudes, we can conclude a clear need for innovative datasets which can address bicycle safety and promote safe design for micromobility.

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CHAPTER FOUR: LAB DEVELOPMENT & SIMULATOR DESIGN

4.1 LAB INTRODUCTION & LAYOUT

In the fall of 2018 a team of faculty, graduate students, and undergraduate students began to envision and enact a VR lab space. The team consists of the following people:

- Faculty: Dr. Donna Chen, Dr. Arsalan Heydarian, Dr. Brian Smith
- Graduate Students: Erin Robartes, Austin Angulo, Xiang Guo
- Undergraduate Students: Emily Chen (graduated), Matt Dean (graduated), Chris Lee (current)

Since 2018 the lab in Thornton Hall room D108 has been established as the Omni-Reality and Cognition Lab (ORCL), a space used to house the VR equipment for the studies described in this dissertation, as well as those for other future driving simulator, VR, augmented reality, etc. studies. The intent is for this laboratory space to foster collaboration on research relating to a broad swath of topics, beginning with transportation behavioral research. More information about the lab and its researchers is available on the ORCL website. https://engineering.virginia.edu/omni-reality-and-cognition-lab. Based on a design by the lab team, the ORCL was renovated from fall 2019 through summer 2020, creating a workspace, meeting space, and research testing area. The lab now consists of two large open spaces. One side houses desks to be used by researchers, an area set up with the computing equipment (computer, monitors) to run the virtual experiments, and a driving simulator. The other space contains the physical equipment for the bicycle simulator and more desks. The open area for the pedestrian simulator spans the entire room (the right side of the room in *Figure 2*). There are also two large television screens so that the researchers can clearly observe the virtual environment as it is being seen by the participant using the simulator. *Figure 2* gives a schematic of the lab layout.

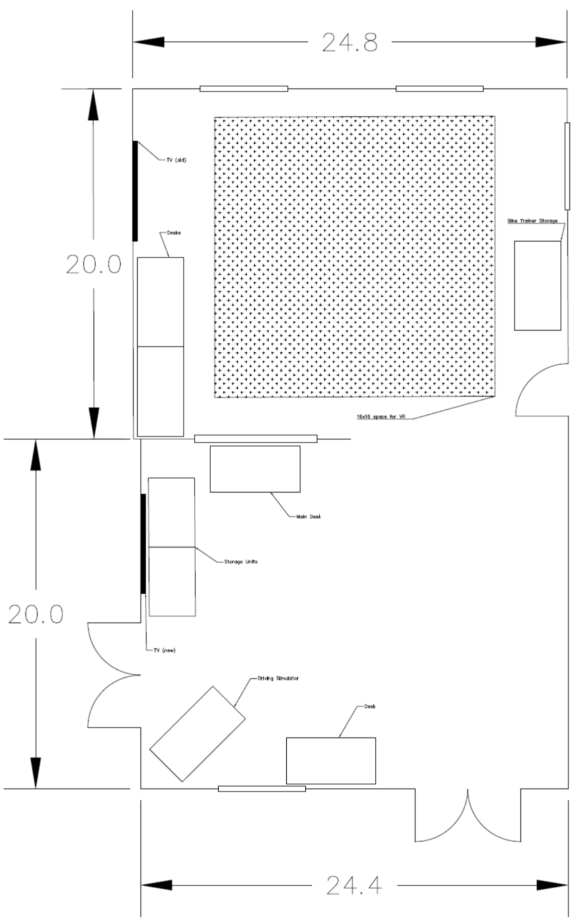

Figure 2. The Omni-Reality and Cognition Lab Layout (Drawing produced by Austin Angulo with AutoDesk).

The extensive amount of equipment used to build the bicycle simulator can be divided into a few broad categories: computing equipment, VR equipment, and bicycle specific equipment.

4.2 COMPUTING EQUIPMENT

Unity software is used to build and display the VR environment. Unity is run through the SteamVR platform and rendered on a high-speed computer with 4K monitors. High performance factory overclocked Nvidia 1080Ti graphics cards run through Scalable Link Interface, an Intel Core i9-7920X, 64 GB of DDR4 RAM at clock speeds of 3600MHz, and M.2 Solid State Hard Drives were installed within the computer. These components allow the computer to render the detailed VR environments at high frame rates. Additionally, an Alienware laptop has been setup to run Unity in order for the setup to be more mobile.

Figure 3. HTC Vive, Computer, and Monitors

4.3 VIRTUAL REALITY EQUIPMENT

VR headsets are used to allow the participants to view the virtual environment. An HTC Vive Pro and an HTC Vive Pro Eye headset have both been tested in the lab, the latter allows for eye tracking of the participants. The HTC Vive Pro Eye headset is one of the first widely available VR headsets to seamlessly incorporate eye tracking capabilities using TobiiPro technology. Prior to 2020 this kind of headset simply did not exist on the market, eliminating the possibility of eye tracking research in VR simulation, due to the inability to wear both an eye tracking and a VR headset. The use of eye tracking in a bicycle simulator is a novel component of the equipment in this lab. The headsets are used in conjunction with HTC Vive Controllers which allow the user to engage with the virtual environment. Additionally, SteamVR Base Stations track the location of the headset and controllers through physical space (*Figure 4*) allowing their location to be translated to the virtual environment. Typically, when using virtual reality equipment, the controllers are held by the user. In the case of our bicycle simulator, the controllers are attached to the handlebars of the stationary bike with Velcro (so that they may be easily removed for charging. This allows for two critical cyclist actions to be detected, steering and braking. The movement of the controllers in space when the cyclist turns handlebars is translated into direction changes in the VR environment. Additionally, the controllers have a trigger on the back, pulling the trigger on the right-hand controller triggers a deceleration of the cyclist in the virtual environment. This method for detecting steering and braking through the use of the virtual reality equipment itself, is another novel element of our bicycle simulator. Additionally, Wireless Adapters and Power Banks are used with the headsets to allow experiment participants to be free from wires that could distract from the virtual experience.

Figure 4. HTC Vive Pro headset, controllers, and base stations.

4.4 BICYCLE EQUIPMENT

For the bicycle simulator setup, two bikes were purchased from a local bike shop, both are the Trek Verve 1. One is a men's large and the other is a women's medium. According to the Trek website, the bikes may be described as follows, "Verve 1 is an introductory hybrid bike designed for comfort on recreational rides. It has a lightweight aluminum frame, a padded saddle, wide tires for extra stability, and 21 speeds." This style was chosen because it is comfortable for a wide range of people and keeps the rider in a fairly upright and comfortable position. The smaller bike will be used for participants who require a smaller bike frame. Additionally, because the smaller bike has a lowstep (*Figure 5*) it will enable those who are less mobile but still capable of riding, to more easily mount the bike. Aside from these differences, the bikes provide a very similar feel. The stationary bike is attached to several pieces of equipment purchased from Wahoo Fitness, an indoor cycling trainer company. The equipment includes a Wahoo Kickr Climb which replaces the front wheel of the bike and can be adjusted vertically to simulate changes in grade on the road. A Wahoo Kickr Smart Trainer replaces the back wheel of the bike. The Smart Trainer provides resistance to the cyclist and is capable of recording speed, power, and cadence. The Smart Trainer is also equipped with Bluetooth, and is compatible with the Unity software which displays the virtual environment. In this way, when a participant pedals on the stationary bike, their speed is translated smoothly into the virtual environment. Additionally, the setup includes a Wahoo Kickr Headwind which is a fan that is positioned directly in front of the bicycle. The fan is connected via Bluetooth to the Kickr Smart Trainer and increases in power the faster the user is pedaling.

Figure 5. TREK Verve 1 Bikes.

4.5 ADDITIONAL SENSORS

The bicycle simulator setup also includes two video cameras which have been setup head on, and facing the side of the bicycle. These cameras allow for body movement analysis. Finally, two smartwatches are worn by the user of the bicycle simulator, one on each wrist. These smartwatches capture heartrate and hand movements and serve as a novel form of data collection in bicycle simulation literature.

4.6 VIRTUAL ENVIRONMENT DESIGN

The virtual environment is one of the most key design elements of the bicycle simulator because it can significantly impact the realism of the experience. In order to achieve a highly detailed rendering based on a real-world location, a team of consultants was hired to develop the VR environment in Unity. Unity is a game engine development platform, and can be used to produce highly detailed and realistic virtual environments. The consultants for the project were Dot Dream LLC. Working with Dot Dream involved an initial goal of recreating a real-world location in VR, followed by numerous iterations as our team tested the environment.

Specifications about the roadway environment were provided to Dot Dream, including lane widths, sidewalk dimensions, distances between each intersection, and dimensions of streetscape elements (signs, fire hydrants, lane markings, etc.) to ensure that the environment was scaled appropriately. Additionally, photographs of textures in the environment were provided to the consultants for them to incorporate into the VR environment, including building facades, roofs, sidewalks, asphalt, among others. Car sounds and ambient noise are also included to further the realism. Certain elements of the environment needed to be dynamic which required coding specific controlled actions. This includes the motor vehicles present in the VR environment, which are the only moving objects in the VRE besides the user. With regards to the cyclist, the motor vehicles do not respond to any cyclist behavior (e.g. if a cyclist moves in front of a car, it will not stop), rather the motor vehicles are programmed at the same speed, follow a straight track along the road, and the types of motor vehicles (color, model) and spacing between each motor vehicle, follow an order provided to the system when the VR environment is opened. The base environment built by Dot Dream was modified to include other bicycle infrastructure (a bike lane and a protected bike lane) for additional experiments.

After being closed for much of 2020 due to the global pandemic, as of fall 2020, the ORCL was fully renovated, set up, and ready for experimental testing with the bicycle simulator. Pilot testing resumed during December of 2020 through January of 2021, and full experimental testing began in February of 2021. *Figure 6* shows the complete bicycle simulator setup including the bike, the Wahoo equipment, sensing equipment, and virtual reality equipment. The computing equipment falls outside this field of view.

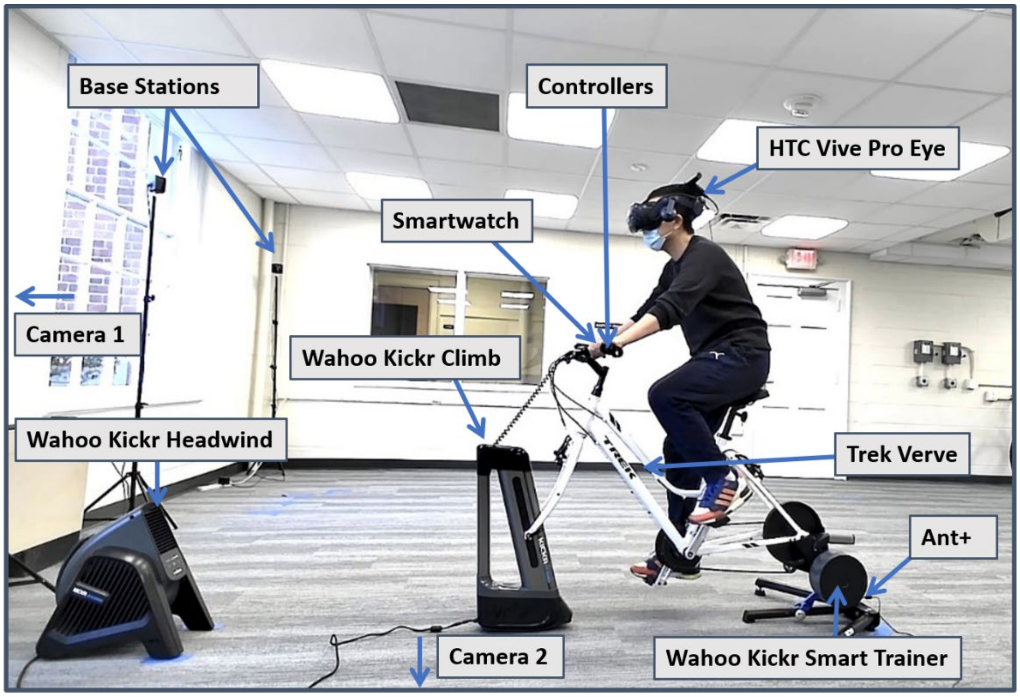

Figure 6. Bicycle Simulator Setup

CHAPTER FIVE: BENCHMARKING STUDY

5.1 BENCHMARKING STUDY INTRODUCTION

The benchmarking study trials a validation method using video collection to capture real world cyclist data and a VR bicycle simulator to capture cyclist data in VR environments. Cyclist behavior from the real-world dataset and the VR simulation dataset are compared to determine how similarly cyclists behave between the two environments. Additionally, during the VR simulator experiment, a survey was administered to the participants, collecting data on their perception of realism of the simulator components. Through these two steps, 1) comparison of cyclist behavior in the real-world and in the VR simulator and 2) responses to questions about the realism of the bicycle simulator, this work provides a framework for the validation of a VR bicycle simulator.

The first step to completing this study was to select a real-world study location that could also be replicated in VR. For this purpose, the researchers engaged in a process to select a corridor for long-term bicycle and pedestrian studies in the city of Charlottesville, Virginia. Corridors were considered based on their existing bicycle infrastructure, room for improvement, safety history, and interest from the city. Based on these factors, the chosen corridor was East Water Street, from the intersection of 2nd Street Southwest to 2nd Street Southeast, directly south of the downtown pedestrian mall (*Figure 7)*. The corridor is well-trafficked by cyclists, has a high pedestrian influx from the nearby pedestrian-only corridor, has been considered by the City of Charlottesville for redesign, and identified as a pedestrian "priority crash cluster" by Virginia Department of Transportation (VDOT). The chosen section consists of two city blocks, there is a 4% downhill grade eastbound, a parking lane in the westbound direction, and there are shared lane markings in both directions. Additionally, the intersection of E Water Street and 2nd Street SE is signalized.

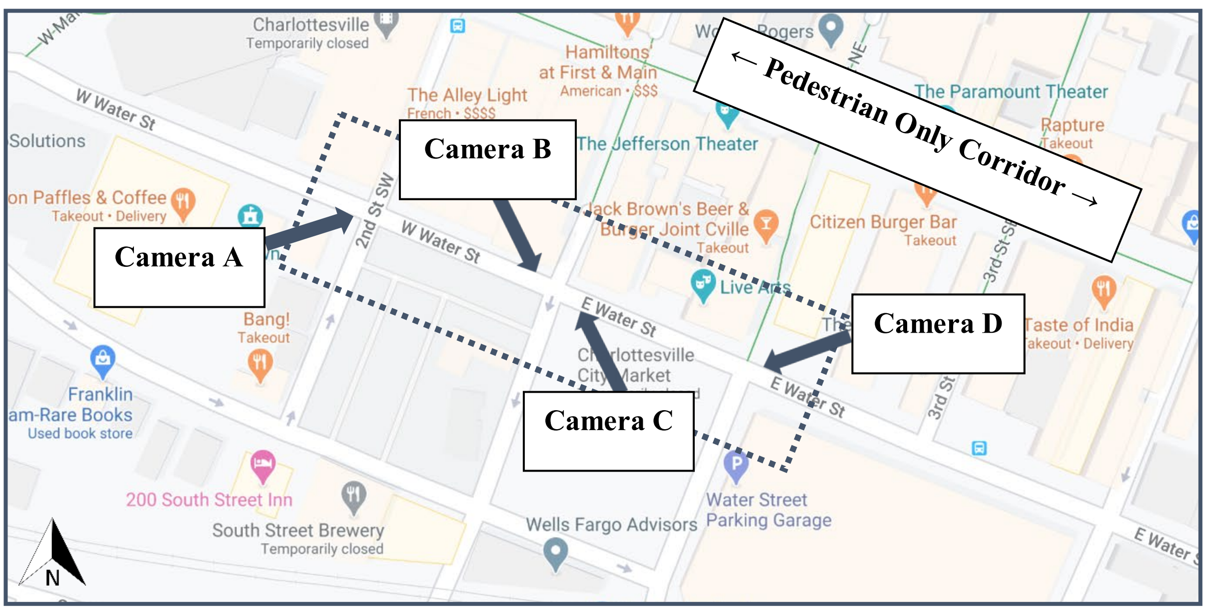

Figure 7 Study location: Water Street in Charlottesville, Virginia (29).

In order to use the VR equipment, the corridor needed to be replicated in a virtual environment (*Figure 8*). The researchers worked with consultants to design this virtual environment over the course of 2019-2020. *Figure 8* provides a visual comparison of the real-world Water Street location and the recreated virtual environment in the Unity platform.

Figure 8 Comparison between Water Street in Google Streetview (left) with the virtual environment in Unity (right).

5.2 REAL-WORLD VIDEO FOOTAGE COLLECTION

From August 27th to 29th and from September 5th to 5th in 2019, four cameras were set up at intersections on the Water Street Corridor. One was set up at 2nd Street SW, two at 1st Street S, and one at 2nd Street SE (*Figure 7*). Two cameras were chosen for the middle intersection to better capture traffic in both directions. The dashed boundary in *Figure 7* indicates the extent of Water Street considered in the study, and the arrows show the direction and location of each camera. The video footage was collected Tuesday through Thursday over two consecutive weeks, resulting in a total of 144 hours of footage.

The 144 hours of footage then needed to be coded into usable data for analysis. Initially, automated detection algorithms were tested to determine if efficient and automatic methods could be used to extract the data. The video footage was ultimately too low quality to utilize computer vision techniques to detect cyclists, cars, or any information about their speed and movement. Therefore, data extraction was completed manually by two independent researchers. The researchers reviewed the video footage and recorded events of interests and their characteristics in spreadsheets. *Table 2* shows the type of information the researchers recorded: where the cyclist was located (if they traversed the entire corridor or part of it) and at what time they entered and departed the corridor (based on the timestamp when the front wheel of the tire contacted specific crosswalks along the corridor). Any interactions of note were recorded in detail (including if a pedestrian crossed in front of the cyclist, or if the cyclist was passed by or passed an automobile or another cyclist). In addition, the cyclist's behavior at the signalized intersection on the east side of the corridor was noted (whether or not the cyclist stopped, and where in relation to the stop bar and crosswalk they stopped).

To record the events and characteristics, the researchers watched the footage from the four cameras simultaneously after adjusting the videos for minor differences in timestamps. For the sake of efficiency, data was only coded during the 7:00 AM - 9:00 AM morning peak period and during the 4:00 PM -6:00PM evening peak period. With six full days of video footage over the two-week video recording period, this method (of only coding peak hours) resulted in 24 hours of video footage being manually coded. The researchers recorded the events and characteristics about them according to the data dictionary (*Table 2*). The two sets of records were cross-checked against each other and conflicting events were removed from the dataset.

Table 2 Event characteristics synthesized from video recordings.

Data Dictionary			
Characteristic		**Input**	**Definition**
Date		mm/dd/yy	Date stamp on camera

Start	Time	hh:mm:ss	Time stamp when front wheel of bicyclist first touches crosswalk or when bicyclist stops at light at 2nd St SE
	Position	1	2nd St SW (east side of east crosswalk)
		2	1st St S (west side of WEST crosswalk)
		3	1st St S (east side of EAST crosswalk)
		4	2nd St SE (west side of west crosswalk)
	Camera	A	Start position was viewed on camera A
		B	Start position was viewed on camera B
		C	Start position was viewed on camera C
		D	Start position was viewed on camera D
End	Time	hh:mm:ss	Time stamp when front wheel of bicyclist first touches crosswalk
	Position	1	2nd St SW (east side of east crosswalk)
		2	1st St S (west side of WEST crosswalk)
		3	1st St S (east side of EAST crosswalk)
		4	2nd St SE (west side of west crosswalk)
	Camera	A	Start position was viewed on camera A
		B	Start position was viewed on camera B
		C	Start position was viewed on camera C
		D	Start position was viewed on camera D
Pedestrian	Cross	0	No pedestrian crossed in front of bicyclist
		1	A pedestrian crossed the street in front of the bicyclist
		2	Group crossing of pedestrians in front of the bicyclist
	Response	NA	No pedestrian crossed in front of bicyclist
		0	No observable response
		1	Bicyclist visibly slows
		2	Bicyclist visibly stops
		3	Bicyclist visibly speeds up
Other Bicyclist	Pass	0	No other bicycle present
		1	Other bicyclist passes observed bicyclist
		2	Observed bicyclist passes other bicyclist
	Response	NA	No other bicycle present
		0	No observable response
		1	Bicyclist visibly slows
		2	Bicyclist visibly stops
		3	Bicyclist visibly speeds up
		4	Observed bicyclist moves over
Vehicle	Pass	0	No vehicle pass
		1	Vehicle passes bicyclist
		2	Bicyclist passes vehicle
	Event	NA	No vehicle pass
		0	No observable change in bicyclist behavior
		1	Bicyclist moves closer to curb
		2	Bicyclist visibly slows down

		3	Bicyclist visibly stops
		4	Bicyclist visibly speeds up
		5	Vehicle passes bicyclist in presence of parked car
		6	Vehicle passes bicyclist just after parked cars
		7	Other?
2nd St SE Signal	Stop	0	Does not stop at signal
		1	Bicyclist stops at signal
	Location	1	Stops at stop bar
		2	Stops at crosswalk
		3	Stops further back from stop bar
		4	Stops in front of crosswalk

5.3 VR BICYCLE SIMULATOR EXPERIMENT

5.3.1 Bicycle Simulator Setup & Pilot Study

The VR bicycle simulator used in the benchmarking experiment was described in detail in Chapter Three. As discussed above, the simulator consists of an instrumented stationary bike with HTC Vive controllers attached to the handlebars, the front wheel replaced with the Wahoo Kickr Climb, and the back wheel replaced with the Wahoo Kickr Smart Trainer. The user is wearing an HTC Vive Pro Eye headset and two smartwatches, one on each wrist. The lab is also setup with one video camera head-on with the participant, one video camera facing the side of the participant (90 degrees from the first) and a fan in front of the bike to simulate wind (*Figure 6*). Using the HTC Vive Headset, the participant is able to view the virtual environment, which replicates the current roadway geometry environment on Water Street (*Figure 8*). This includes the lane widths, grade, lane striping, signage and traffic signal.

The entire experimental procedure was pilot tested between December 2020 and January 2021, and the full in-person VR benchmarking experiments took place during February and March of 2021 under strict COVID-19 safety protocols. The complete transcript used to guide each participant through the study was tested and modified iteratively during the pilot studies. The written test script may be found in Appendix D.

5.3.2 Consent Form

Once participants have indicated interest in participating in the research study they must then agree to the participant consent form (Appendix B). This form details the goals of the research study, what will occur during the research study, the participant's right to withdraw at any time, and their compensation. The consent form was distributed to the participant via email prior to their arrival for the research study (Appendix A). The consent form is completed through Qualtrics Survey Software, the participant provides a virtual signature and a copy of the form is returned to them. This is separate from any other collected data so that the other surveys remain anonymous.

5.3.3 COVID-19 Protocols

A health screening was administered via phone to each participant within 24 hours of their scheduled experiment. A second health screening was administered verbally upon their arrival to the lab in person. The results of both health screenings were recorded electronically using the University of Virginia health screening website. Masks were worn by participants and researchers at all times, doors were kept open to increase ventilation (except when outdoor noise would impact the immersion of the virtual experience) and 6-feet of space was maintained between everyone in the room when possible. All equipment (bicycle, headset, controllers) and frequently touched surfaces (keyboard, mouse, desk, chair, doorknobs) were sanitized between each participant. A minimum of one hour was scheduled in between participants to ensure time for cleaning even if the previous experiment ran longer than expected.

5.3.4 Pre-Experiment Questionnaire

A pre-experiment questionnaire was also administered to the participants upon their arrival to the lab. It was also completed through Qualtrics Survey Software using a laptop setup in the lab. The full questionnaire may be reviewed in Appendix C. The purpose of this survey is to collect information about the participant, their typical transportation habits, experience and comfort with bicycling, experience with VR, car and bike ownership, and socio-demographic questions.

5.3.5 Bicycling Experiment

After completing the survey phase (safety screening, consent form, and pre-experiment questionnaire) of the experimental protocol, the researcher present would explain the rest of the experiment, describe the data being collected, and give the participant a chance to ask questions. Each of the participants completed the bicycle simulator experiment and a pedestrian simulator experiment which was being run concurrently. The pedestrian experiment will not be discussed here, but a description can be found in the test script (Appendix D). The order of the bicycle or the pedestrian phase of the experiment was randomized. As described in the test script, before beginning the bicycle experiment the research assistant would explain the components of the bicycle simulator, how to pedal, brake, steer, and how to use the headset. The participants then use the simulator to cycle through a familiarization environment so that they can learn how to use the simulator. Familiarization is critical to teach the participant to appropriately use the pedals, brakes, and steering during the experiment, particularly because they cannot see the physical bicycle they are using due to the HMD. Pedaling is highly intuitive, however braking requires learning to locate the controller trigger which initiates braking in VR, and steering requires adjusting to the motion of turning the handlebars without the tilt that normally accompanies steering in real life. Once participants felt comfortable navigating the familiarization environment, they were placed in a series of three VR environments. The three environments consist of an as-built environment (no bike infrastructure aside from sharrows), one with an unprotected bike lane, and one with a protected bike lane (pylons). For each environment the participant is instructed to calibrate the steering before pedaling (by turning the handlebars right, left, and back to center), to bike down the road to the second traffic signal, and then to use the brake to come to a stop before being pulled out of the VR environment.

In the VR environments, each participant was exposed to either high-volume or low-volume traffic for the entirety of the experiment. These volumes were both based on the real-world traffic levels on Water Street. High-volume traffic was determined by observing the peak-hour traffic on Water Street and approximating this volume using a distribution of gap sizes between motor vehicles. The low-volume traffic was simply half the volume as modeled by the high-volume traffic.

5.3.6 Post-Experiment Questionnaire

After completing the cycling experiment, the participants were asked to fill out a post-experiment questionnaire. This questionnaire is again completed on a laptop in the room using Qualtrics Survey Software. This questionnaire collected information about whether the participant experienced motion sickness, how realistic they felt the various components of the simulator were, how realistic they felt their own movement was in VR, and how safe they felt in the virtual environment they experienced. The full questionnaire is available in Appendix C.

5.4 RESULTS

The following section begins by describing the two datasets used to validate the simulator: the real-world video footage and the VR experiment datasets. This is followed by a comparison between characteristics of the cyclists in the two datasets. Finally, the survey questions asking about realism of the VR simulator which were given to the VR experiment participants are discussed.

5.4.1 Participant Characteristics

5.4.1.1Real-World Video Footage Sample

As previously discussed, the real world dataset consists of cyclists and their behaviors that have been manually coded from the video footage. The dataset initially included all cyclists that cycled for at least one block on Water Street in Charlottesville between 2nd St SW and 2nd St SE. This dataset was then pared down to consist only of cyclists whose experience would most closely reflect the experience of the participants in the VR experiments. Therefore, only cyclists from the video footage were included that traveled Eastbound on Water Street, who biked the full length of the study corridor (2nd St SW to 2nd St SE), and who did not stop at the signal at the 2nd St SE intersection. This is because in the VR environment, participants bike the full corridor Eastbound, and the signal is always green in the virtual environment. This is the extent of data cleaning for the real-world sample because no other information (e.g. demographics, characteristics) could be obtained due to the nature of the data collection. Resultantly, the real-world video footage dataset has a sample size of N=90.

5.4.1.2 VR Simulator Experiment Participants

More information is known about the VR experiment participants because they completed a pre-experiment questionnaire containing socio-demographic questions. Primarily email, social media, and word of mouth were used to recruit the participants. All participants were required to be over the age of 18 and capable of riding a stationary bike. The initial dataset included 51 participants, however, one was unable to complete the experiment due to motion sickness, resulting in a sample size of N=50 (female=23, male=27, mean age=34.14 years, median age=30 years). One participant did not provide their age in the pre-experiment survey, the age distribution of the remainder of the participants (N=49) is shown in *Figure 9*.

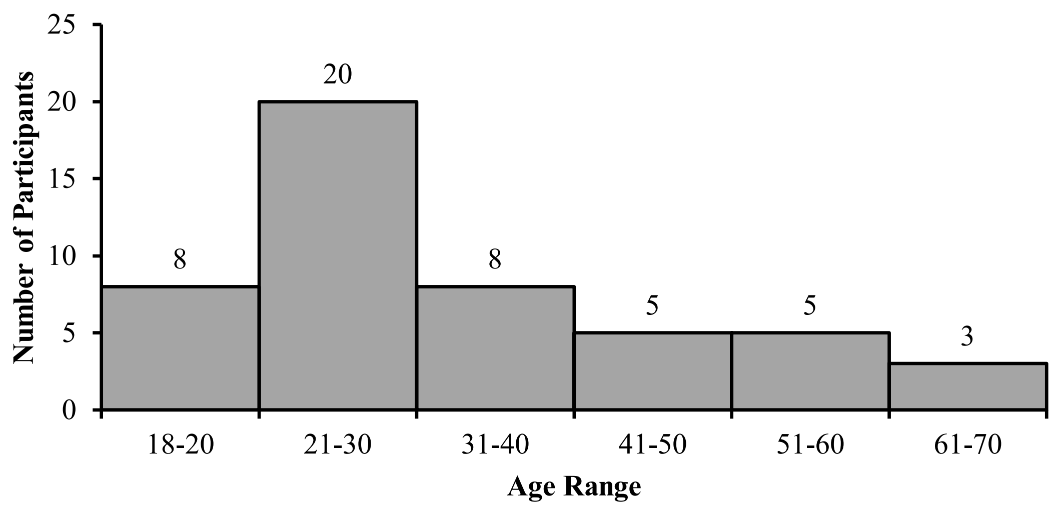

Figure 9 Histogram of participants' ages (N=49).

Additional cyclist characteristics were considered, including participants' attitude toward biking as measured by "Geller's Four Types of Bicyclists" via the pre-experiment questionnaire (*Geller, 2006*). Two participants reported that they do not bike (*Table 3*). For the analyses comparing cyclist behavior in the real-world environment to the cyclist behavior in the VR environment, these two participants were excluded from the VR participant pool (N=48, female=22, male=26, mean age=34.6, median age=30). This was done to make the VR participant pool more closely reflect the real-world bicyclists on Water Street. For additional analyses which involved the traffic in the environment, the traffic data was not recorded correctly for one VR experiment participant, and was excluded (N=47, female=21, male=26, mean age=34.7, median age=30).

Table 3 Pre-experiment questionnaire – bicycling attitudes.

What describes your attitude toward biking?	Percent of Responses (N=50)
"Strong and Fearless" – I will ride anywhere, no matter the facilities provided	18%
"Enthused and Confident" – I like to ride and will do so with dedicated infrastructure	52%
"Interested but Concerned" – I like the idea of riding but have concerns	26%
"No way, no how" – I do not ride a bike	4%

5.4.2 Real-World and VR Data Comparison: Speed Analysis

The first characteristic compared between the real-world and VR experiment datasets is the speed of the cyclists. This component will help to verify that the virtual reality cyclists move through the virtual space in a similar way to the real-world cyclists. For the real-world cyclists, average speeds on the corridor were calculated using timestamps from the cameras on Water Street. For the VR participants, speeds were collected continuously by the simulator. The average speed between 2nd St SW and 2nd St SE was calculated to compare to the real-world cyclists. The two participants who recorded "I do not ride a bike" on the cycling attitude question were excluded from the VR subset because that bicycle classification would not be found in the real-world subset. Speed histograms for the real-world cyclists and VR cyclists are shown in *Figure 10*. Similar speed distributions for the two subsets show that the VR environment was well scaled and VR participants moved through it similarly to those in the real-world environment. Absolute validity between the real-world speed (M = 14.161 mph, SD = 2.67 mph, N = 90) and virtual reality speeds (M = 14.996 mph, SD = 3.93 mph, N = 48) can be verified as there is no statistical difference between the two datasets via a two sample t-test (t[70.757] = 1.317, p =0.192) (Appendix E). Additionally, a Kolmogorov–Smirnov test could not reject the null hypothesis that the two samples may be from the same distribution (p=0.14).

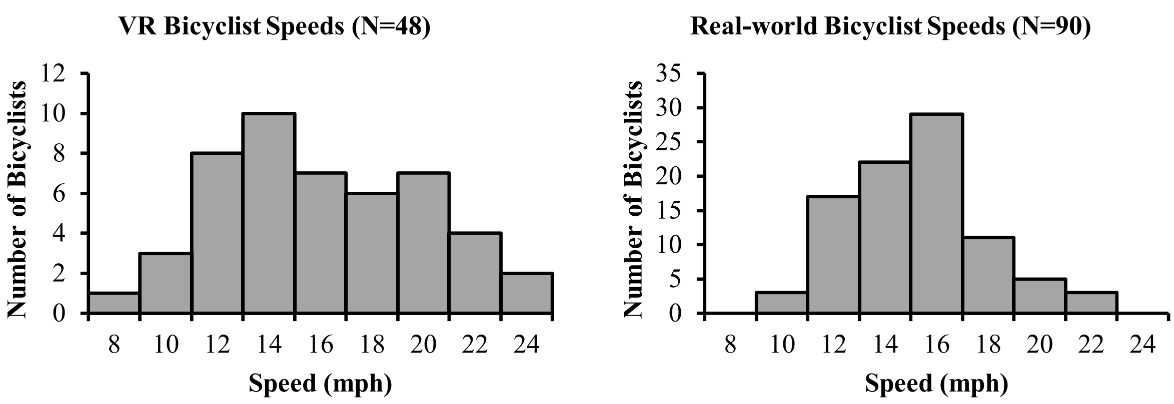

Figure 10 Histograms of real-world (left) and in-lab (right) bicyclist speeds.

5.4.3 Real-World and VR Data Comparison: Car Passing Analysis

An additional element that could be extracted from the video-footage dataset for comparison was the interaction between motor vehicles and the cyclists. In both the real-world and VR environments there are motor vehicles present. The number of cars in the VR environment was based on the video footage collected from Water Street. Traffic volume in the VR environment was intended to replicate real-world conditions by creating a distribution of gap sizes between cars from peak-hour travel from the video footage. The peak-hour distribution was classified as the high volume scenario (correlating to approximately 572 veh/hr). A low volume scenario was developed by doubling the gap sizes between cars (approximately 286 veh/hr). In the VR environment, participants were exposed to either the high (peak-hour) volume or low volume scenario. In the VR environment, motor vehicle speeds were standardized at 25mph, the posted speed limit on the road. The two traffic volumes (high and low) used in the experiment replicate two different bicycle levels of service (BLOS). The real-world Water Street corridor varies in width along the section of the corridor used for this study. The BLOS for the corridor under the high volume conditions varies from B to D depending on the width of the section of corridor. Under the low volume condition, the BLOS varies from B to C along the corridor. BLOS quantifies how comfortable a cyclist may be (on a scale of A-F) on a road based on physical characteristics of that road and the traffic environment. *Figure 11* shows the number of passing events experienced by cyclists in the real world and in VR.

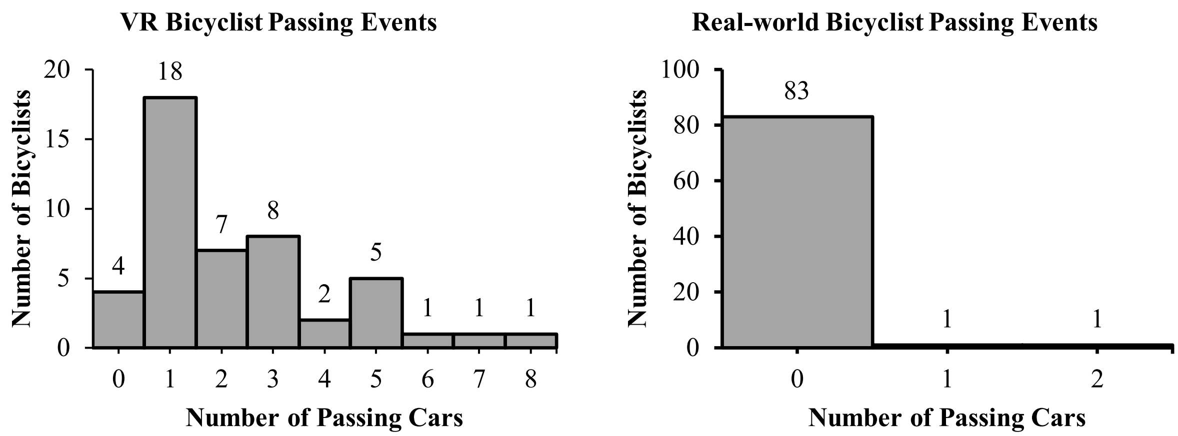

Figure 11 Histograms of the number of passing events experienced by bicyclists in the VR and real-world datasets.

As a result of the motor vehicles present in the real-world and VR environments, cyclists experienced passing events while traversing the corridor. The number of events where cyclists are passed by cars is higher for participants in the VR environment (varies between 0 and 8) compared to the real-world environment (varies between 0 and 2 cars). Additionally, the sample size of real-world cyclists who experience passing events is very small compared to the cyclists in the virtual environment (only two cyclists were passed by cars) (*Figure 11*).

Relative speed between the real-world and VR cyclist datasets can also be compared by studying the impact on speed as it relates to an external factor such as motor vehicle passing events. For each group of cyclists who experienced the same number of passing events, the average speed of that set of cyclists was found. The number of passing events and the corresponding average speeds of all the cyclists who experienced the same number of events is shown in *Figure 12*. Cyclists in the real world and VR environments experience similar intuitive consequences, when they bike more slowly, more cars will pass them.

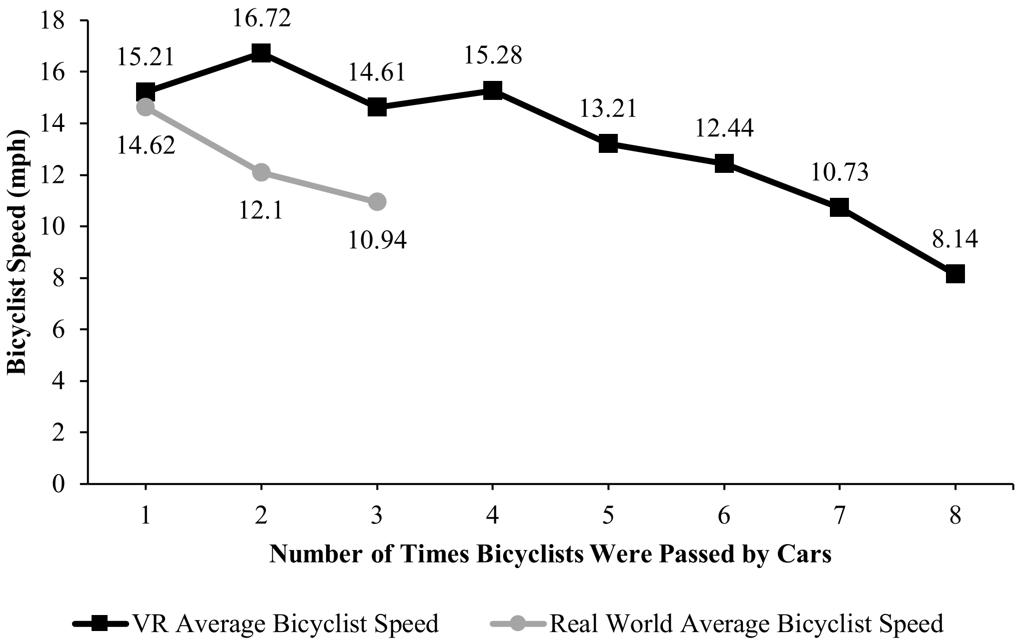

Figure 12 Average speed of bicyclists by number of passing events

As is logical, in both the real-world and VR environments, cyclists experienced more passing events when traveling at lower speeds. However, the cyclists in the VR environment experienced many more passing events than the cyclists in the real-world. Some VR participants experienced up to 8 passing events on the three blocks between 2nd St SW and 2nd St SE, whereas no real-world cyclist experienced more than 2 passing events. Because the cyclist speeds have been shown to be similar in the real-world and VR environments, this variation in traffic experience is likely a result of how the VR vehicle-traffic was designed. For example, in VR, the speed of the virtual traffic is the same for all vehicles all the time. This does not account for real-world driver behavior. For example, in the real-world, when a driver approaches a cyclist from behind they may slow down and wait for an opportune moment to pass them. This driver response is not captured in the VR environment.

Increased passing events shows that the driver behavior on this specific corridor is not fully captured by the VR environment. This could present an opportunity for improving the vehicle traffic environment in future iterations of experimentation. For example, vehicle volumes were replicated from the Water Street video recordings, and a similar process could be followed to replicate speeds, rather than setting a uniform speed for all vehicles. Alternatively, analysis of real-world driver speeds could show whether using the speed limit of the road was an accurate depiction of real-world speeds; perhaps the simulated speed was simply too high, leading to more passing events for cyclists.

5.4.4 Survey Results

After VR experiment participants were finished using the simulator, they were asked to complete a post-experiment questionnaire. This included questions about their perceived realism of various components of the simulator. The following table shows the questions posed to the participants, and the distribution of responses to each question. Each question was answered using a Likert scale from 1 to 5, where 1 is “not at all” and 5 is “very”. For the first question, “How realistic was the bicycle steering?”, a response of 1 would mean “not at all realistic”, and 5 would mean “very realistic”.

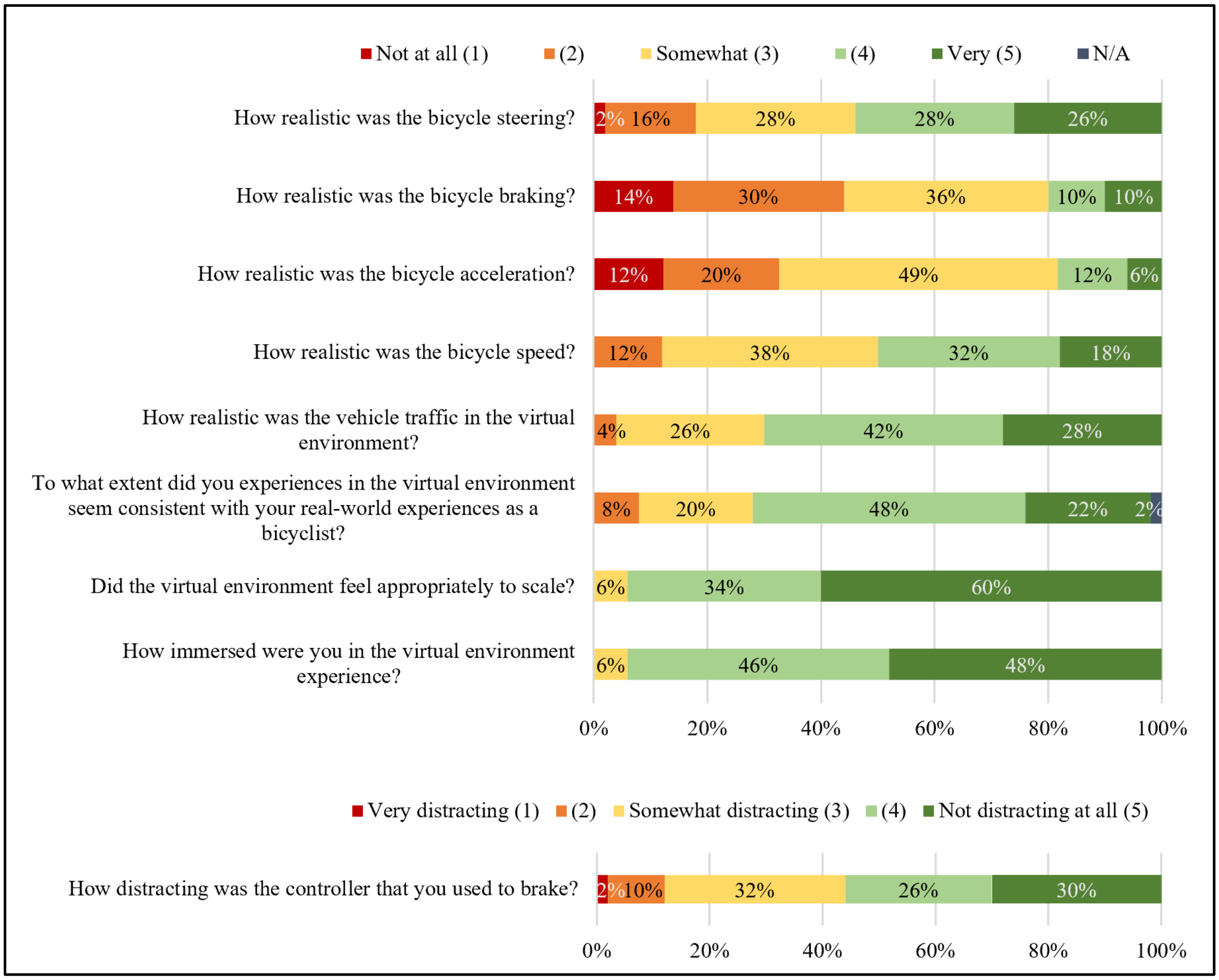

Figure 13 VR Bicycle Experiment Post-Experiment Questionnaire Responses

The responses to the post-experiment questions on realism reveal that participants overall felt positively about the realism, but pointed out certain elements that could be improved (*Figure 13*). The majority of participants felt that the virtual environment was immersive, with 94% of participants rating it a 4 or 5 on the 5-point Likert scale (mean=4.42), Most participants also found that the virtual environment was to scale (94% chose 4/5, mean=4.54) and consistent with their real-world experiences as a bicyclist (70% chose 4/5, mean=3.86). Most participants also felt that the vehicle traffic (70% chose 4/5, mean=3.94), their speed (50% chose 4/5, mean=3.56), and their steering were realistic (54% chose 4/5, mean=3.60). Participants found the bicycle acceleration (18% chose 4/5, mean=2.80) and the bicycle braking (20% chose 4/5, mean=2.72) to be the elements most lacking in realism. This may relate to the braking mechanism (controller) mounted on the bicycle handlebars, or the way braking and acceleration are modeled in the virtual environment. As previously mentioned, the brake consists of a trigger on the controller, and the dissimilarity of this device compared to a regular bicycle hand brake would naturally contribute to the diminishing realism of bicycle braking experience in VR. Alternatively, this could also relate to how acceleration and deceleration is modeled in the virtual environment. The brake does not transmit a strong deceleration force, which is required to replicate the physics of real-world cycling. Some participants may be used to a stronger braking power from their own cycling experience in real world conditions. Nonetheless, these results show that the majority of the participants felt that most of the simulator components were realistic. The elements reported by participants as lacking in realism should be improved in future experiments.

5.4.5 Other Results

In Chapter Six, "Bicycle Infrastructure and Perceived Safety Experiment" more data was analyzed from the experiment that supports both chapters five and six. The data in chapter six covers not only the as-built bicycling environment which mirrors the real-world Water Street corridor in Charlottesville, but also covers two other bicycling environments which were modified to change the bicycling infrastructure to a bike lane in one environment and a protected bike lane in the other. Several results from the analysis of these three environments in chapter six add credence to the benchmarking study. These results and their implications for the benchmarking study will be discussed in chapter six.

5.5 CONCLUSIONS

This study aims to bridge a significant research gap in the bicycle simulator research domain by creating a benchmarking methodology for VR bicycle simulators. This methodology included the collection of two datasets for comparison. The real-world data came from video footage of 90 cyclists on Water Street in Charlottesville, Virginia. The VR simulator data came from the 50 experiment participants who cycled on a stationary bike while immersed in a scale replica virtual environment of Water Street. The quality of the video footage limited the analysis possible for validation, however two key characteristics were compared between the real-world video footage data and the VR data. Speed distributions between the real-world and VR data were directly compared, and absolute validity between the two datasets was determined. While slower cyclists in both the real-world and the VR environment were both passed by more vehicles, the vehicle traffic behavior in the VR environment did not replicate that of the real world. Therefore, no validity can be confirmed when comparing passing behavior. Finally, the participants from the bicycle simulator experiment completed a questionnaire which asked them questions about realism of the simulator. A majority of participants found the simulator components and the VR experience to be realistic, particularly in terms of the immersiveness of the environment. Most participants (70%) also felt the VR experience was consistent with their real-world experiences as a cyclist.

One limitation of this study relates to the difficulty in recruiting participants during the COVID-19 pandemic. Even with COVID-19 safety precautions in place, participants are risking exposure to COVID-19 by choosing to participate in the experiments. Those who choose to participate may be less risk averse, or consider themselves less at risk of COVID-19 (e.g., younger and healthier). Targeted outreach was necessary to achieve a wide range of ages among participants. This may also be a product of the experiments being conducted in a college town where younger participants (e.g., students) are more readily available. In terms of the real-world cyclist data, as mentioned, the video quality did not allow for more rigorous analysis of cyclist behavior on Water Street. Additionally, characteristics of the real-world cyclists such as age and gender were not known. The distribution of those characteristics among the real-world cyclists could differ from those of the VR experiment participants.

Future work will involve validating the bicycle simulator using more detailed physiological and body position data collected from instrumented bicyclists cycling along the Water Street corridor in Charlottesville. This will allow for a stronger comparison between real-world and in-lab cyclists by taking advantage of the extensive amount of data that can be collected from the VR bicycle simulator.

5.6 REFERENCES

Geller, R. Four Types of Cyclists. Portland Bureau of Transportation, Portland, Ore., 2006. http://www.portlandoregon.gov/transportation/article/264746. Accessed July 6, 2021

CHAPTER SIX: BICYCLE INFRASTRUCTURE AND PERCEIVED SAFETY EXPERIMENT

6.1 INTRODUCTION

The following experiment on bicycle infrastructure and its impact on perceived safety achieves several goals. First, this experiment illustrates a methodology for using the bicycle simulator to evaluate different roadway environments. This method could be used to study roadway environments for project evaluation, for studying novel roadway environments that do not exist in real life, or for studying roadway environments that are too dangerous to study in real-life conditions. Additionally, the types of bicycle infrastructure chosen for the study are typical for US roadways and their impacts on perceived safety are intuitive and established. This allows us to compare the results using this experimental methodology with those of traditional methodologies, lending additional support to the benchmarking analysis.

The experimental design for this study relied on perceived safety literature as described in Chapter Two which shows that the roadway environment, including space allocated to the cyclist, can have an impact on how safe a cyclist feels. In order to understand how VR can be used to assess perceived safety, using the virtual environment replica of the Water Street corridor, research participants followed an experimental protocol intended to elicit different perceptions of safety due to changes in the roadway environment and traffic volumes. In summary, this experiment serves to develop a new VR experimental methodology and compare the results to existing research. The following sections describe the experimental design, the virtual environments, and the participants.

6.2 EXPERMENTAL DESIGN

The experiments used to complete the benchmarking study as described above in section 5.3 are the same experiments used for this bicycle infrastructure and perceived safety study. The key difference being that several VR environments through which the participants cycled were not used for the benchmarking study, but are discussed here as part of this study. As described above, in-person experiments took place in February and March of 2021, under COVID-19 protocols resulting in 51 participants, with 50 completing the full study. Participants completed two health screenings and a pre-experiment questionnaire upon arrival in the lab. The pre-experiment questionnaire included questions on demographics, recent travel history, bicycling attitude, motor vehicle and bicycle ownership, and familiarity with VR. After completing the questionnaire, participants used the bicycle simulator to cycle first through a familiarization environment without vehicle traffic to learn how to use the simulator. Once the participants felt comfortable using the simulator, they cycled through the three different bicycle infrastructure design alternatives (sharrows, bike lane, and protected bike lane). The order in which each participant cycled through the three environments was randomized (within-subject factor). The as-built environment with sharrows is the VR environment that was previously analyzed in the benchmarking study. Each participant was exposed to either low-volume or high-volume traffic for the entirety of the experiment (between-subject factor) as described in section 5.4.3. After completing the cycling experiment, the participants complete a post-experiment questionnaire. This questionnaire included questions on motion sickness, realism of the simulator components, realism of their own movement in VR, and perceptions of safety in each environment. The entire experimental procedure was pilot tested between December 2020 and January 2021, and full experimentation was completed between February and March of 2021.

6.3 BICYCLE INFRASTRUCTURE ALTERNATIVES

The virtual environment in the three infrastructure scenarios is identical except for the bicycle infrastructure. Water Street is a two-lane road, with on-street parking in the westbound direction. The three infrastructure environments consist of an as-built environment (as the road exists in real life with no bicycle infrastructure except for painted sharrows), an environment with bike lanes in the eastbound direction, and an environment with protected bike lanes in the eastbound direction. The bike infrastructure modeled in the virtual environments are based on standard design guidelines, including the image of the sharrow, the width of the bike lanes, and the design of the bollards in the protected bike lane. Images of the three environments are shown in *Figure 14*. In each environment, the participant starts just before the intersection of Water Street and 2nd Street SW. The bicycle steering is calibrated, and then the participant is instructed to bike to the second traffic signal at the end of the road (eastbound).

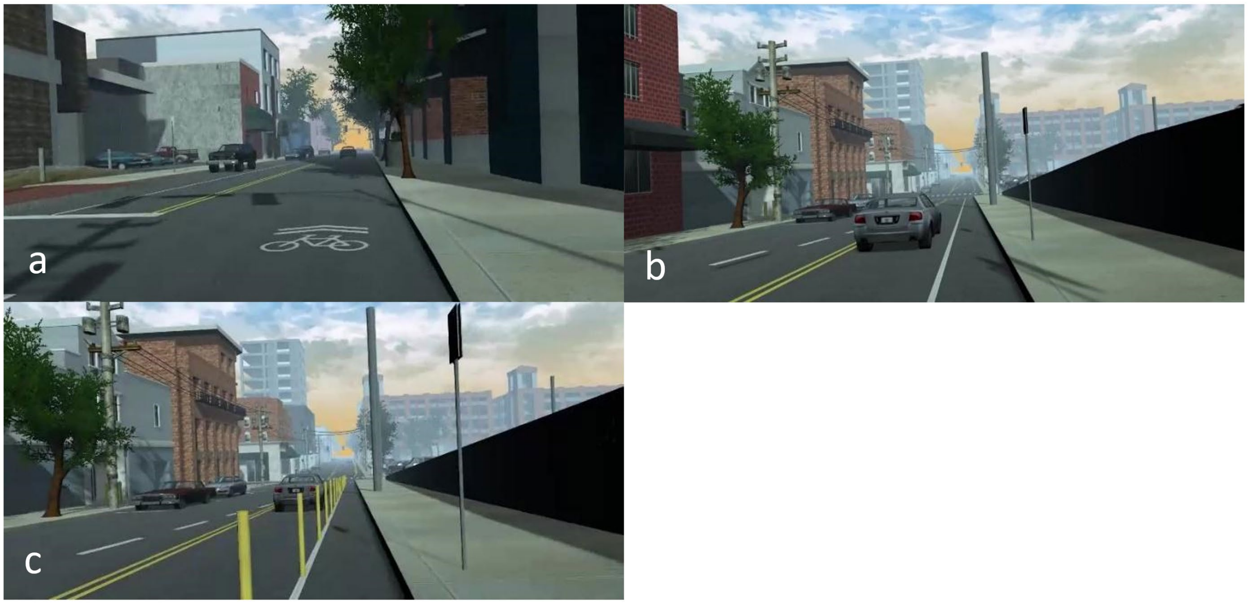

Figure 14 Environment with sharrows/as-built (a), environment with bike lanes (b), and environment with protected bike lanes (c).

6.4 SURVEY RESULTS

6.4.1 Stated Preference Surveys: "How safe did you feel using the different kinds of bike infrastructure?"

Responses to stated preference survey questions after experiencing each environment in VR were used to assess differences in perceived safety between environments with different bicycle infrastructure. On a scale of 1-5 (Not safe at all [1] to Somewhat Safe [3] to Very safe [5]) respondents were asked how safe they felt using the different kinds of bike infrastructure. The mean for the as-built scenario (sharrows) was 2.60. For the bike lane and protected bike lane, the mean increased to 3.9 and 4.12, respectively (*Table 4*).

Table 4 Descriptive statistics for "How safe did you feel using the different kinds of bike infrastructure?"

	Mean	Std. Deviation	N
As Built (Sharrows)	2.60	1.195	50
Bike Lane	3.90	0.763	50
Protected Bike Lane	4.12	1.100	50

6.4.1.1 Within Subjects Effects

Histograms of the responses to the question "How safe did you feel using the different kinds of bike infrastructure?" may be seen in *Figure 15*. In this section and in several of the following sections, parametric tests are used to analyze the Likert scale survey data. In the literature there is some controversy on whether parametric or nonparametric tests are the most appropriate way to analyze Likert scale data. Some experts conclude that parametric tests are sufficiently robust such that they may provide reliable results even when statistical assumptions such as normality are violated (*Sullivan and Artino, 2013; Norman, 2010*). As a result, this dissertation makes use of parametric tests for Likert scale data analysis. Repeated measures ANOVA was used to compare the means of perceived safety measures between the three environments.

Sphericity was not met, and univariate tests were used to adjust. Mean levels of feelings of safety differ significantly between the three environments (as-built, bike lane, protected bike lane) ($F(1.376, 67.436) = 29.918$, $p=0.000$). Pairwise comparison using Bonferroni correction shows an increased feeling of safety in the bike lane compared to the as-built environment (3.9 compared to 2.6, $p < 0.001$). Additionally, there is an increase in feelings of safety in the protected bike lane compared to the as-built environment (4.12 compared to 2.6, $p < 0.001$). There is no statistically significant difference between the slightly higher level of safety in the protected bike lane compared to the unprotected bike lane ($p = 0.693$). For full results see Appendix F. The stated preference survey results imply that a separated space for bicyclists such as a bike lane or protected bike lane improved feelings of perceived safety for participants. This is consistent with results from previous literature, using non-simulation methods (*Chataway et al., 2014; Nevelsteen et al., 2012*).

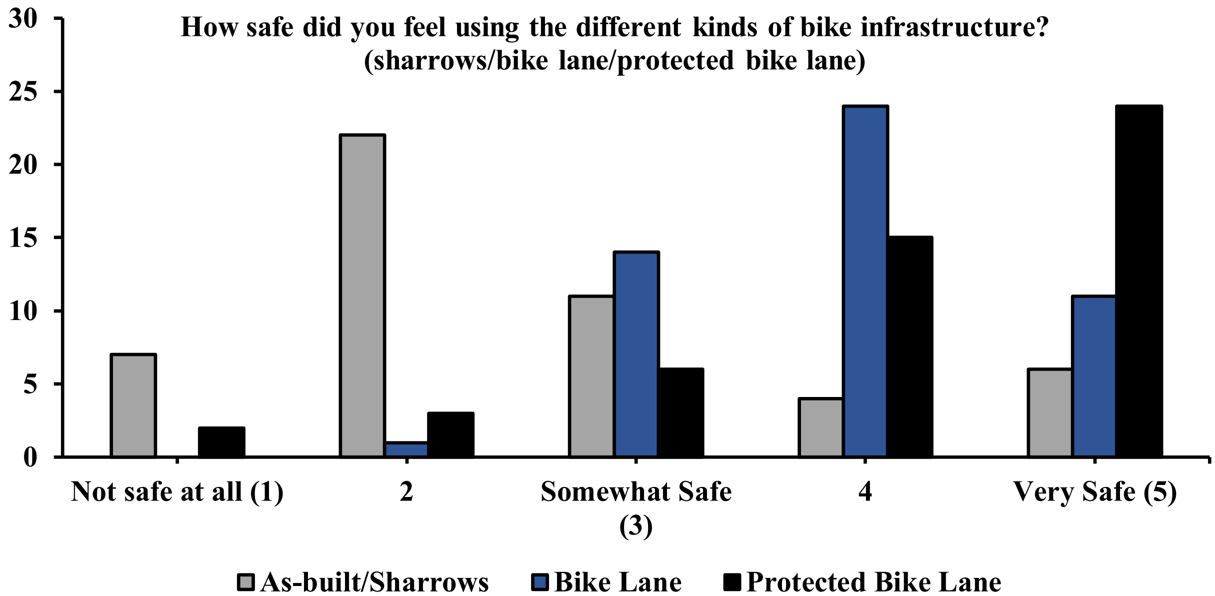

Figure 15 Histograms of responses to "How safe did you feel using the different kinds of bike infrastructure?"

6.4.1.2 Between Subjects Effects

High and Low Vehicle Volume Effects

All participants in the study experienced all three environments. The participants were split into two groups, some experiencing high volume traffic (N=26) which imitated peak hour traffic volumes on Water Street, and the rest experiencing low volume traffic (N=24) which was half of the peak hour traffic volume. The descriptive statistics for responses to the perceived safety questions, split by traffic volume condition, are shown in *Table 5*. and the responses to the same questions (on a scale of 1-5, not safe at all to very safe) are shown in *Figure 16*.

Table 5 Descriptive statistics for responses to "How safe did you feel using the different kinds of bike infrastructure?" split by bike infrastructure and traffic volume environment.

Environment	Traffic Volume	Mean	Std. Deviation	N
As-Built	High	2.50	1.140	26
	Low	2.71	1.268	24

Bike Lane	High	4.00	.800	26
	Low	3.79	.721	24
Protected Bike Lane	High	4.27	.827	26
	Low	3.96	1.334	24

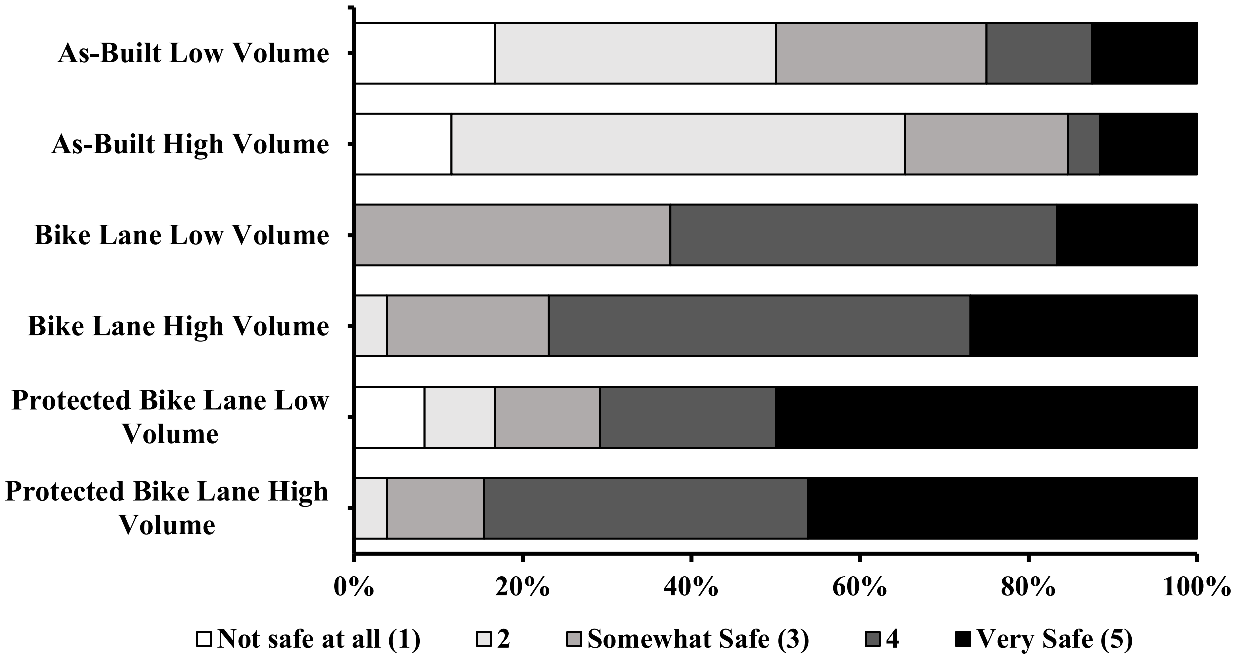

Figure 16 Responses to "How safe did you feel using the different kinds of bike infrastructure?" split by bike infrastructure and traffic volume environment.

Repeated measures ANOVA for perceived safety responses for the three environments were run with traffic volume as a between-subjects effect. The interaction factor of traffic volume with the perceived safety responses for environments were not significant.

To further investigate how volume was involved in the perceived safety responses, the high volume sample and the low volume sample were analyzed separately. For the high volume sample, a repeated-measures ANOVA determined that the mean levels of feelings of safety differ significantly between the three environments: as-built, bike lane, protected bike lane ($F(1.585,39.62) = 28.996$, $p <0.001$). The pairwise comparison using Bonferroni correction shows an increased feeling of safety in the bike lane compared to the as-built environment (4.0 from 2.5, $p < 0.001$). Additionally, there is an increase in feelings of safety in the protected bike lane compared to the as-built (4.27 from 2.5, $p < 0.001$).

Results are similar when only looking at the participants who received the low volume scenarios compared to the entire sample. A repeated-measures ANOVA determined that the mean levels of feelings of safety differ significantly between the three environments: as-built, bike lane, protected bike lane ($F(1.214, 27.92) = 7.491$, $p <0.05$). The pairwise comparison using Bonferroni correction shows an increased feeling of safety in the bike lane compared to the as-built environment (3.79 from 2.71, $p < 0.05$). Additionally, there is an increase in feelings of safety in the protected bike lane compared to the as-built (3.96 from 2.71, $p < 0.05$).

From the high volume participants there is a greater spread between the safety ratings of the bike lane/protected bike lane environments and the as-built environment compared to the ratings from the low volume participants. Additionally, the differences have a higher level of significance for the high volume participants. However, the perceived safety ratings do follow the same trend in both the high volume and low volume groups (perceived safety ratings are higher in the bike lane and protected bike lane environments compared to the as-built environment). The two different BLOS levels modeled by the high and low traffic volumes may play some role in the resulting perceived safety measures.

Gender Effects

The impact of gender on responses to perceived safety questions was also examined, descriptive statistics may be seen below (*Table 6*) Repeated measures ANOVA for perceived safety responses for the three environments were run with gender as a between-subjects effect.

Table 6 Perceived safety question descriptive statistics for male and female cyclists in each VR environment.

Environment	Gender	Mean	Standard Deviation	N
As-Built	Female	2.17	.717	23
	Male	2.96	1.400	27
Bike Lane	Female	3.96	.767	23
	Male	3.85	.770	27
Protected Bike Lane	Female	4.43	.945	23
	Male	3.85	1.167	27

The sample included 23 female and 27 male participants. Males rate the as-built scenario as safer than females whereas females rate the bike lane and protected bike lane safer than males. The interaction effect between gender and the environment on perceived safety response was significant ($p=0.01$), so the data was split between males and females and the perceived safety responses between environments were examined.

For both the female and male groups, the perceived safety values are significantly different between the three environments ($F[1.66,36.527]=43.063$, $p=0.00$ and $F[1.229,31.95]=5.679$, $p=0.018$ respectively). Pairwise comparisons using Bonferonni correction determine that for the female group the perceived safety values differ significantly between the bike lane and the as-built environments and between the protected bike lane and as-built environment ($p=0.000$, $p=0.000$ respectively). For the male group, only the perceived safety means for the bike lane and as-built environments are statistically different ($p=0.003$). Differences between male and female cyclists in terms of their comfort, risk aversion and perceived safety have been well established. Female cyclists' have shown higher levels of fear of traffic compared to male cyclists (*Chataway et al., 2014*), and a greater preference for off-road paths than on-road bicycling compared to male cyclists (*Garrard et al., 2008; Heesch et al., 2012*). Findings from this study show that protected bike lanes significantly increase female cyclists' perception of safety compared to the road with no bike lanes; this result is not observed for male cyclists. Bike lanes significantly increase both male and female cyclists' perceptions of safety compared to a road with no bike lanes. See Appendix F for full results.

Bicycling Attitude Effects

Participants were asked to self-report their attitude toward cycling using Geller's "Four Types of Bicyclists" during the pre-experiment questionnaire (*Geller, 2006*) which was previously discussed in *Table 3*.

Repeated measures ANOVA for perceived safety responses for the three environments were run with bicycling attitude as a between-subjects effect. The category of "No way, no how" was removed due to the low sample size, and the interaction factor of attitude with perceived safety responses for the environments was not significant. We can conclude that in this sample bicycling attitude does not significantly impact differences in responses to perceived safety questions for each environment.

6.4.2 Stated Preference Survey: "How safe did you feel concerning the cars driving past you while you were biking in the bike lane/biking in the protected bike lane with pylons/biking in the road with no bike infrastructure?"

In the previous section, responses to the question "How safe did you feel using the different kinds of bike infrastructure?" were studied. This section follows the same method to analyze responses to the question "How safe did you feel concerning the cars driving past you while you were biking in the bike lane/biking in the protected bike lane with pylons/biking in the road with no bike infrastructure?" Again, participants could respond on a scale of 1 (not safe at all) to 5 (very safe). The mean response for the as-built scenario was 2.5, for the bike lane the mean response was higher at 3.54, and for the protected bike lane the response was found to be even higher at 4.34 (*Table 7*).

Table 7 Descriptive statistics for "How safe did you feel concerning the cars driving past you while you were..."

	Mean	Median	Standard Deviation	N
As Built	2.5	2	1.136	50
Bike Lane	3.54	4	1.024	50
Protected Bike Lane	4.34	5	0.886	50

6.4.2.1 Within Subjects Effects

Histograms of the responses to the question "How safe did you feel concerning the cars driving past you while you were…?" may be seen in *Figure 17***.** Repeated measures ANOVA was used to compare the means of traffic safety measures between the three environments. Mean perception of traffic safety ratings differ significantly between the three environments (as-built, bike lane, protected bike lane) ($F(2,98) = 44.586$, $p<0.001$). Pairwise comparison using Bonferroni correction show the mean responses to the traffic safety questions are all significantly different from each other. The feelings of safety regarding traffic in the protected bike lane and bike lane environments are significantly higher than that in the as-built environment (4.34 compared to 2.5 , $p<0.001$ and 3.54 compared to 2.5, $p < 0.001$ respectively). Additionally, there is a further increase in feeling of safety regarding traffic in the protected bike lane compared to the bike lane (4.34 compared to 3.54, $p < 0.001$). Mean feelings of safety regarding traffic were significantly different in the protected bike lane compared to the bike lane (The stated preference survey results imply that a separated space for bicyclists such as a bike lane or protected bike lane improved feelings of perceived safety regarding motor vehicles for participants. See Appendix F for full results.

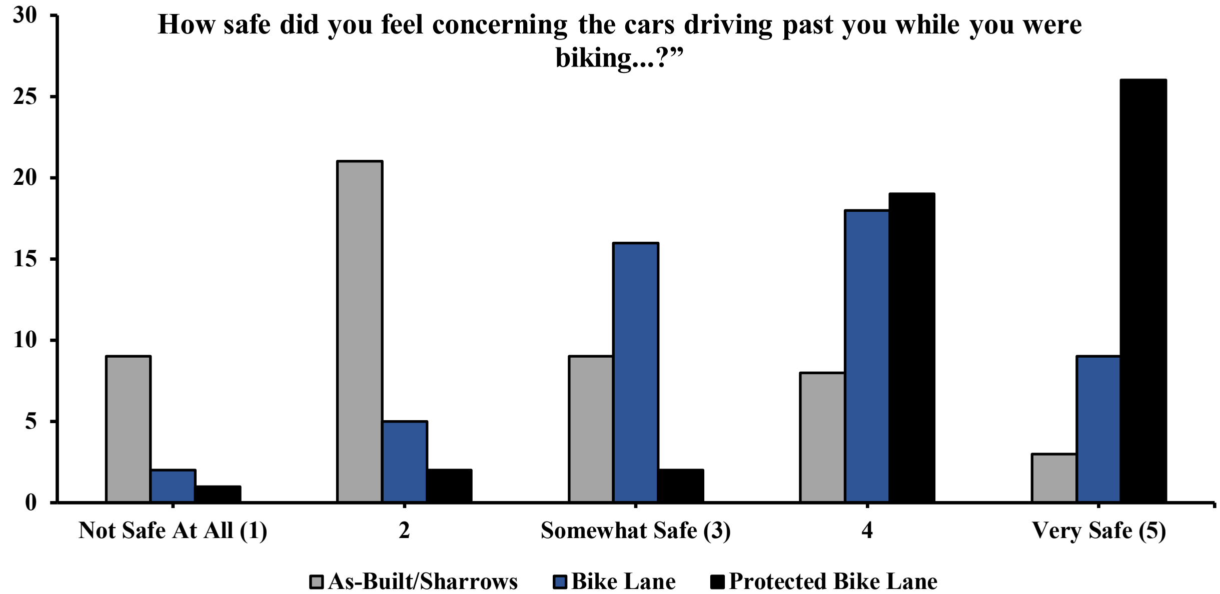

Figure 17 Histogram of responses to "How safe did you feel concerning the cars driving past you while you were…"

6.4.1.2 Between Subjects Effects

High and Low Vehicle Volume Effects

As previously mentioned, all participants in the study experienced all three environments and each participant was assigned into one of two groups, one group experienced high volume traffic (N=26) and the other experienced low volume traffic (N=24). As was found in the previous section regarding the perceived safety question, when ANOVA was used to evaluate high and low volume on the responses to the traffic safety question in each environment, no significant differences were found between high and low volume participants. When high and low volume groups were separated, and repeated measures ANOVA were run, for both groups the same results were seen as in the entire population (means feelings of safety regarding traffic are significantly different between all environments). However, the differences between means are larger for the high volume participants than the low volume participants (*Table 8*). See Appendix F for full results.

Table 8 Descriptive statistics for "How safe did you feel concerning the cars driving past you while you were…" by traffic volume.

Environment	Traffic Volume	Mean	Std. Deviation	N
As-Built	High	2.46	1.104	26
	Low	2.54	1.215	24
Bike Lane	High	3.58	1.137	26
	Low	3.50	0.933	24
Protected Bike Lane	High	4.46	0.859	26
	Low	4.21	0.932	24

Gender Effects

The impact of gender on responses to traffic safety questions was also examined to compare male (N=27) and female (N=23) responses to traffic safety questions about each environment. Descriptive statistics for male and female average responses to the traffic safety question may be seen in *Table 9*.

Table 9 Descriptive statistics for "How safe did you feel concerning the cars driving past you while you were…" by gender.

Environment	Gender	Mean of traffic safety question response	Standard Deviation	N
As-Built	Female	2.30	1.105	23
	Male	2.67	1.177	27
Bike Lane	Female	3.52	1.039	23
	Male	3.56	1.050	27
Protected Bike Lane	Female	4.39	0.941	23
	Male	4.30	0.869	27

On average, female cyclists rate the as-built and bike lane as less safe with regards to traffic than male cyclists rate them and the protected bike lane as safer with regards to traffic than male cyclists rate it. However, a repeated measures ANOVA of mean responses to traffic safety questions with the between-subject factor as gender shows that there is no significant interaction between gender and the traffic safety responses in each environment $F(2,96) = 0.719$, $p=0.490$. See Appendix F for full results.

Bicycling Attitude Effects

Participants were asked to self-report their attitude toward bicycling using Geller's "Four Types of Bicyclists" during the pre-experiment questionnaire (*Geller, 2006*).

Table 10 Descriptive statistics for "How safe did you feel concerning the cars driving past you while you were…" by bicycling attitude.

Environment	Bicyclist Attitude	Mean of traffic safety question response	Standard Deviation	N
As-Built	Interested but Concerned	2.31	1.182	13
	Enthused and Confident	2.38	1.169	26
	Strong and Fearless	3.22	0.972	9
Bike Lane	Interested but Concerned	3.46	0.877	13
	Enthused and Confident	3.58	1.172	26
	Strong and Fearless	3.67	0.866	9
Protected Bike Lane	Interested but Concerned	4.38	0.506	13
	Enthused and Confident	4.35	1.018	26
	Strong and Fearless	4.22	1.093	9

From *Table 10* it may be observed that less confident cyclists ("interested but concerned") report mean safety ratings for the as-built and bike lane environments than "enthused and confident" or "strong and fearless" cyclists. However, repeated measures ANOVA for traffic safety responses for the three environments were run with bicycling attitude as a between-subjects effect. The category of "No way, no how" was removed due to the low sample size, and the interaction factor of attitude with traffic safety responses for the environments was not significant. We can conclude that in this sample bicycling attitude does not significantly impact differences in responses to traffic safety questions for each environment. Existing literature has found that cycling attitude does impact perceptions of safety. Bill et al., (*2015*) for example found that novice/intermediate cyclists typically had higher risk perceptions of hazards than experienced cyclists. The results of our study appear to follow this trend, and may lack statistical significance due to low sample sizes. See Appendix F for full results.

6.4.3 "The three bicycling environments you experienced are listed below. Please select the one in which you felt the LEAST SAFE and the one in which you felt the SAFEST:"

The final question asking about perceived safety of the three environments asked participants to report the environment in which they felt the least safe and the environment in which they felt the safest. The results of this question may be viewed in *Table 11*. From this table it can be seen that the majority of participants (80%) felt that the as-built environment with the sharrow road markings was the least-safe environment. The majority of participants (70%) also felt that the protected bike lane was the safest environment. However, this question also reveals the differences among the bicycling community, 4 participants (8%) felt that the as-built environment, which only has lane markings to remind motor vehicles that cyclists can share the road, was the safest. And 7 participants (14%) felt that the protected bike lane, the only environment with a physical barrier between the cyclists and the vehicles, was the least safe. There is a subset of cyclists who will not use bicycle infrastructure when it exists and prefer to use the roadway as a motor vehicle would. In some cases, cycling in the center of the road can be a tactic to avoid motor vehicles passing a cyclist. These differences in cyclist behavior reflect the challenge of designing bicycle infrastructure, and the need to understand the differences in people who use it. Some cyclists may feel at home in a lane with motor vehicles which allows them to bike faster and unencumbered by additional infrastructure. Others, may feel most comfortable with a physical barrier separating them from cars. Neither population can be ignored and all types of cyclists must be considered when designing roadways and creating policy that governs them.

Table 11 The number of responses in each category to the question "The three bicycling environments you experienced are listed below. Please select the one in which you felt the LEAST SAFE and the one in which you felt the SAFEST:" N=50.

	As-Built	Bike Lane	Protected Bike Lane
Least Safe	40	3	7
Safest	4	11	35

6.5 BICYCLE SIMULATOR OUTPUT RESULTS

6.5.1 Speed Results

The previous sections primarily analyzed survey responses and their relationship with cyclist characteristics. In addition to the survey data, the experiment involves collection of data from the bicycle simulator itself. The data collection system for the bicycle simulator records information about the cyclists' position in the environment (in x, y, z coordinates), positions of the controllers in the environment (x, y, z coordinates), engagement with the buttons on the controllers (including the trigger which signifies braking), the position of the headset (x, y, z coordinates), speed, power, and timestamps for every row of data. In this section, the speed data from the simulator will be discussed.

For the three environments, speed data was collected from each participant using the Wahoo Kickr Climb output. Speed is assessed for each participant between the first crosswalk and the first traffic signal along the road. This is to avoid any impact of delayed startup, or early slowing down at the end of the roadway. This ensures a clear start and end point for comparing cyclists and better captures the section of the road where the participant is most immersed. Average speed along the section of road was calculated for each participant. Fifty-one participants were recruited for the bicycling experiment, 50 completed the entire study, there was an error in data collection in one participant, therefore the speed calculations reflect the data for N= 49 participants. A histogram of the average speed for each participant in each environment can be seen in *Figure 18*.

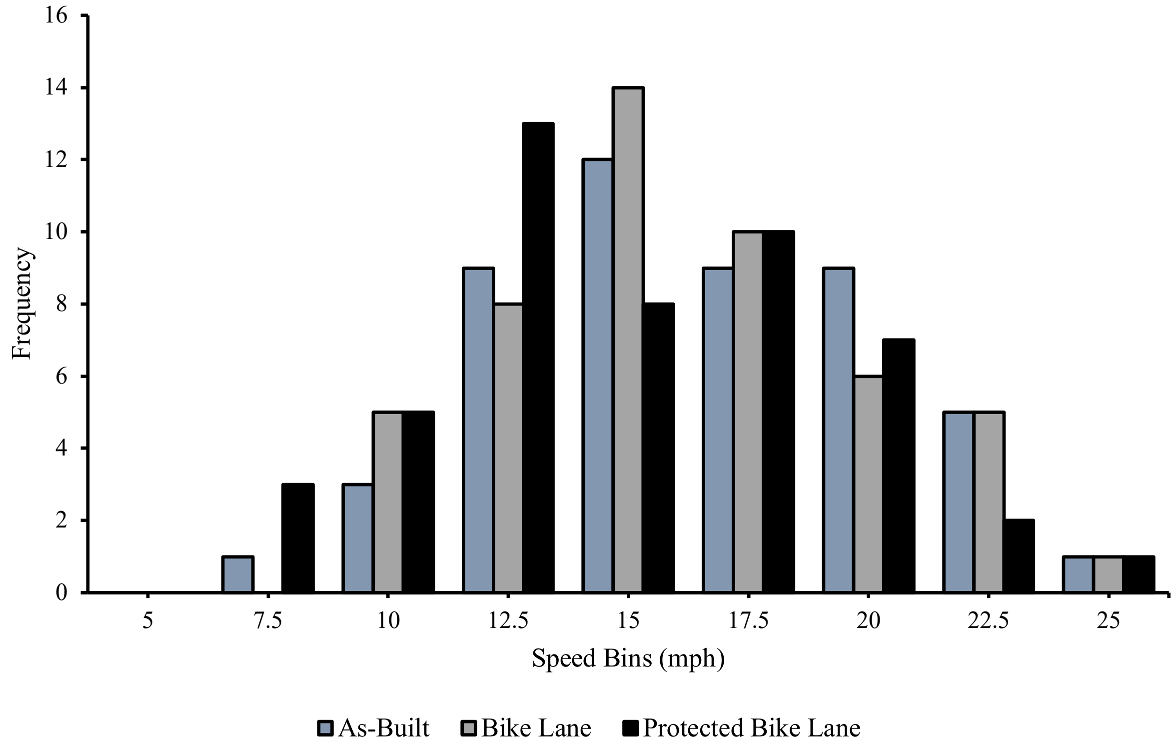

Figure 18 Histogram of participants' mean speed for each cycling environment (N=49).

The histograms for each environment appear relatively normal and similar to each other. A repeated measures ANOVA test was used to determine if there are differences between average speeds in the three environments. Sphericity is met and results show that means between the three speed distributions are significantly different $F(2, 96)=5.822$, $p=0.004$. Pairwise comparisons show that mean speeds in the as-built and protected bike lane environments are statistically different ($p=0.011$). Mean speeds in the bike lane and protected bike lane environments are statistically different only at the $p=0.1$ level ($p=0.052$). Participants travelling significantly slower in the protected bike lane than they do in the as-built environment may be due to the navigation task of staying within the bollards that border the bike lane. Mean and standard deviation of speeds for each environment may be seen in *Table 12*. Full results of the ANOVA speed analysis are in Appendix F.

Table 12 Descriptive statistics of participants' speed for each cycling environment.

	Mean (mph)	Standard Deviation (mph)	N
As-Built Speed	15.094	3.940	49
Bike Lane Speed	14.904	3.768	49
Protected Bike Lane Speed	13.869	4.156	49

To further investigate the speed results, the impact of gender, bicycling attitude, and traffic volumes were assessed. The average speed for males (N=26) and females (N=23) in each bicycling environment can be seen in *Table 13*. On average, female cyclists had higher speeds compared to male cyclists in each environment. Female cyclists also had higher standard deviations in the as-built and bike lane environments. Female cyclists had lower average speeds in the protected bike lane than in the as-built environment ($p=0.025$). For male cyclists, paired t-tests also show lower speeds in the protected bike lane environment compared to the as-built environment ($p=0.068$), they also reveal that male cyclists had significantly slower average speeds in the protected bike lane than in the regular bike lane ($p=0.017$). However, repeated measures ANOVA of the speeds in each environment was run with gender as a between subject effect, and the interaction effect of gender was not found to be significant $F(2,96) = 0.719$, $p=0.490$. Each environment was also examined individually and the speed means for male and female cyclists were compared with t-tests. No statistical differences were found. See Appendix F for full results.

Table 13 Descriptive statistics of male and female cyclists' speed for each cycling environment.

Environment	Gender	Mean Speed (mph)	Std. Deviation (mph)	N
As-Built	Female	15.45	4.10	23
	Male	14.78	3.85	26
Bike Lane	Female	15.17	4.04	23
	Male	14.67	3.58	26
Protected Bike Lane	Female	14.05	4.09	23
	Male	13.70	4.29	26

Similarly, to discern any relevant impact of traffic volume on speeds, repeated measures ANOVA tests were used to compare the speed distributions of participants in each environment, with the traffic condition as a between-subject effect. Descriptive statistics for high and low volume recipients in each environment may be seen in *Table 14*. Those participants receiving the high volume treatment had lower average speeds in the protected bike lane and as-built environments compared to those receiving the low volume treatment. For the participants receiving the high volume treatment, their speeds were lower in the protected bike lane than in the bike lane environment ($p=0.030$) and in the as-built environment ($p=0.018$). The interaction of traffic volume in the ANOVA was not significant, suggesting that traffic volume did not meaningfully impact speeds (Appendix F).

Table 14 Descriptive statistics of high and low traffic volume recipient speeds for each cycling environment

Environment	Traffic Volume	Mean speed (mph)	Std. Deviation (mph)	N
As Built	High Volume	14.78	4.01	26
	Low Volume	15.45	3.92	23
Bike Lane	High Volume	14.97	3.78	26
	Low Volume	14.83	3.84	23
Protected Bike Lane	High Volume	13.41	3.73	26
	Low Volume	14.39	4.62	23

Finally, the participants were asked to characterize themselves in terms of cycling attitude (strong and fearless, enthused and confident, interested but concerned, no way, no how). "No way no how" was excluded from the analysis because only two participants fell into this category. For the enthused and confident cyclists, mean speeds are significantly slower in the protected bike lane than in the bike lane ($p=0.032$) and are also significantly slower in the protected bike lane than in the as-built environment ($p=0.002$). To determine if this characteristic had any effect on participant' speeds a repeated measures ANOVA with between-subject effect of bicycling attitude was used. The attitude interaction effect is not significant. Descriptive statistics for speeds for each bicycling attitude category in each environment are in *Table 15*.

Table 15 Descriptive statistics of bicyclist attitude category speeds for each cycling environment.

Environment	Bicyclist Attitude	Mean Speed (mph)	Std. Deviation (mph)	N
As-Built	Interested but Concerned	13.50	3.14	13
	Enthused and Confident	15.70	3.92	25

	Strong and Fearless	15.20	4.97	9
Bike Lane	Interested but Concerned	13.91	3.08	13
	Enthused and Confident	15.48	3.80	25
	Strong and Fearless	14.70	4.92	9
Protected Bike Lane	Interested but Concerned	13.36	3.39	13
	Enthused and Confident	14.06	3.74	25
	Strong and Fearless	13.72	6.32	9

6.5.2 Braking Results

Braking in the virtual environment is initiated by pulling a trigger on the back of a controller attached to the handlebars of the bike. Pulling the trigger is recorded by the Unity software code, allowing us to capture timestamped data about trigger movements. The variable is coded between 0 and 1, as 0 when the trigger is not being pulled, as 1 when it is being pulled down as much as possible, and in between 0 and 1 when the trigger is partially pulled down. Additionally, this variable is converted to a binary variable where 0 means the trigger is not being pulled and 1 is coded only when the trigger is pulled down hard enough to signify an intent to brake (a very gentle touch of the trigger will not be coded in this case). The continuous braking data between 0 and 1 was used for the following analysis. The average value recorded by participants in each of the three cycling environments is summarized in *Table 16*.

Table 16 Descriptive statistics of participants' average squeeze braking value for each cycling environment.

Environment	Mean	Standard Deviation	N
As Built	0.013	0.038	49
Bike Lane	0.008	0.021	49
Protected Bike Lane	0.022	0.046	49

Repeated measures ANOVA is used to compare average braking values across the three different environments. Sphericity is not met, Huynh-Feldt correction is used, and it is determined that mean braking values are significantly different ($F(1.632,78.316)=2.613$, $p<0.09$). Pairwise comparisons show that the average braking squeeze value is significantly higher in the protected bike lane compared to the bike lane environment ($p=0.049$). As discussed in section 6.5.1, the higher braking values in the protected bike lane (and resultantly the lower speeds in the protected bike lane) may be due to the navigation task of staying within the protected bike lane. The bollards may also impact the perception of width in the bike lane. The protected bike lane is the same width as the bike lane, however, some participants expressed that the protected bike lane felt narrow. Cyclists' have been shown to bike more slowly in narrower lanes (*Vansteenkiste et al., 2013*). Findings from Boufous et al. (*2018*) suggest that cyclists adjust speed to accommodate pedestrians and path conditions, slowing in areas with higher pedestrian volumes and cycling faster on paths with centerlines, wider paths, and paths with visual segregation from pedestrians. Perceived bike lane width and navigation task may explain increased braking values in the protected bike lane environment. The full results of this analysis are in Appendix F.

6.5.3 Lane Positioning Results

Lane positioning of the cyclist was observed using the cyclist coordinate data captured from the bicycle simulator. The x axis is aligned with the direction of the roadway, measuring distance traveled along the roadway. The z coordinate is the vertical distance traveled (for example this value will decrease as bicyclist travels downhill), and the y coordinate is perpendicular to the x coordinate, measuring the lateral distance the cyclist moves in the roadway. To determine the lane position of the cyclist at any moment, the y coordinate of the cyclist and the y coordinate of the curb are used to calculate the cyclists' distance from the curb. This is a meaningful measure because it is a quantifiable measure of cyclist behavior, helping to explain interactions with motor vehicles in the road, comfort with the environment, and the space available to the bicyclist. The mean distance to the curb in the protected bike lane environment is significantly smaller than in the as-built environment ($p<0.1$). Of greater interest, the standard deviation of the distance to the curb in the protected bike lane and separated bike lane are significantly lower than in the as-built environment ($p<0.05$). This indicates that across the participant dataset, bike lanes and protected bike lanes may play a role in helping cyclists maintain a consistent lane position in the roadway. This finding highlights the benefit of simulation techniques over real-world observation, as accurate lane positioning is easily and consistently measured in this simulation.

6.6 CONCLUSION

This study presents an innovative method for analyzing an important element of cyclist safety: perceived safety. Perceived safety helps explain what kind of roadway environment cyclists feel comfortable in. This in turn matters because perceived safety is a barrier to cycling uptake (*Manaugh et al., 2017*), and with increased mode share of cyclists comes a safety in numbers effect (*Jacobsen, 2003; Fyhri et al., 2017*). Additionally, perceived safety has been shown to correlate with actual safety (*Manton et al., 2016*). Actual safety of bicyclists can be hard to measure without comprehensive crash data, which is limited and is a reactive approach to studying safety. Using VR simulation to study perceived safety serves as a proactive tool to better understand cyclists' safety without waiting for crashes to occur. Additionally, VR can be used to safely study cyclists' perceived safety on infrastructure that does not exist in the real-world or that bicyclists' have no experience with. The results from this study cover data from the questionnaires and data retrieved from the bicycle simulator.

Survey results from the study show increased feelings of safety when more space is allocated for the bicyclist on the road (bike lane, protected bike lane) compared to the road without a separated space (as-built with sharrows). This is consistent with results from other methods (*Chataway et al., 2014; Nevelsteen et al., 2012*). This suggests that VR combined with stated preference surveys can reliably assess perceived safety related to bicycle infrastructure.

Additionally, this survey results find differences in how male and female cyclists perceive the safety of bicycle infrastructure, showing female cyclists to feel significantly safer in both protected bike lanes and bike lanes compared to a roadway with only sharrows. Male cyclists perceived the bike lanes to be significantly safer than a roadway with sharrows, however differences between safety perceptions of protected bike lanes were not significantly different than any other roadway infrastructure. This is a reminder of the need to cater to cyclists' expectations of comfort and the need for them to feel safe in order to increase their mode share. It has been documented that women are more risk averse than men, and in the United States men make up the majority of the cycling population. Without bicycle infrastructure which female cyclists perceive to be acceptably safe, the gap in male and female cyclists may continue to persist. Future work will allow us to use the same method with more innovative roadway configurations to understand cyclists' comfort with bicycle infrastructure that they have never used or that is too dangerous to study in real life.

The bicycle simulator outputs included information about speed, braking data, lane positioning. Results showed significant differences in cyclist speeds between different environments. Particularly that mean speeds in the as-built environment are significantly different than those from the protected bike lane environments ($p=0.011$). Mean speeds in the bike lane and protected bike lane environments are statistically different only at the $p=0.1$ level ($p=0.052$). Analysis of the braking data showed that the average braking squeeze value is significantly higher in the protected bike lane compared to the bike lane environment ($p=0.049$). Additionally, looking at the coordinates of the participants in each environment, distance from the curb can be computed for participants' in each environment. The mean distance to the curb of cyclists in the protected bike lane environment is significantly smaller than in the as-built environment ($p<0.1$). Furthermore, the standard deviation of the distance to the curb in the protected bike lane and separated bike lane are significantly lower than in the as-built environment ($p<0.05$). These results reflect the ability of bicycle simulation methods to detect precise physical movement data which would be challenging to gather under real-world conditions.

One limitation of conducting experiments during the COVID-19 pandemic is that participants are risking exposure to COVID-19 even with safety precautions in place, those who choose to participate may be less risk averse, or consider themselves less at risk of COVID-19 (e.g., younger and healthier). Indeed, targeted outreach was required to get a wide range of ages among our participants. Although, this may also be a product of conducting experiments in a college town where younger participants (e.g. students) are more readily available. Because the questionnaires in this study specifically ask about perceptions of safety, it is important to acknowledge that the participant pool may in general be slightly less risk averse than the general public.

Future work in this space would examine more novel types of bicycle infrastructure. In this study, using common bicycle infrastructure (sharrows, bike lanes, and protected bike lanes) allows us to compare results from this study to results from studies using non-simulation methods. Building off this work, new bicycle infrastructure designs which participants are unfamiliar with could also be tested. For unfamiliar infrastructure, participants' ability to use it correctly, willingness to use in the future, and perceptions of safety, would provide researchers with novel data and help planners and engineers understand cyclists' acceptance of new infrastructure.

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CHAPTER SEVEN: CONTRIBUTIONS & FUTURE WORK

7.1 MAJOR CONTRIBUTIONS

The key contributions from this work come from the development of the Omni-Reality and Cognition Lab and the bicycle simulator, the benchmarking methodology, and the bicycle infrastructure and perceived safety experiments.

7.1.1. Simulator Development

One of the key contributions from the simulator development phase of this work is the inclusion of numerous novel components. The literature review of existing bicycle simulators found a lack of integrated, detailed sensing equipment. The headset used in the bicycle simulator is the HTC Vive Pro Eye with Tobii software, the integrated eye tracking software. The use of this headset is the first time to our knowledge that eye tracking has been incorporated into a bicycle simulator. This is due to recent technology innovation and will allow for novel analysis in future experimentation. Incorporating the Wahoo Kickr Headwind introduces another level of immersion by simulating the wind that a cyclist would feel when cycling on a real street. The Headwind, which is part of the Kickr indoor bicycling equipment line, was chosen because it increases in power in response to an increase in speed by the cyclist, increasing realism. The inclusion of smartwatches is another valuable component of sensing equipment element which have rarely been incorporated in bicycle simulation. Two smartwatches are worn by the participant and serve to record heartrate and track hand movements which can be used for body analysis. Video cameras were also incorporated in the lab design so that analysis can include body movements.

One of the recurring problems in bicycle simulation work with VR HMDs is simulator sickness. This is one reason why bicycle simulator labs continue to use screens for visualization instead of HMDs; they are much less likely to induce simulator sickness. Virtual reality simulator sickness symptoms have been shown to be similar to those of typical motion sickness symptoms (*Gavgani et al., 2018*) and in some cases has been found to disproportionately impact female VR users (*Munafo, 2017*). Simulator sickness may be triggered by movement that feels inconsistent with what is expected to happen or by sudden movements (*Sherman, 2002*). Two particular elements of the bicycle simulator that could trigger motion sickness are braking and steering because they result in changes in acceleration and direction respectively. In the ORCL, this was addressed through repeated pilot testing of these elements to make them feel as real as possible and to avoid sudden changes in steering and braking.

A key contribution is developing a method for steering that minimizes motion sickness. As previously discussed, the steering is determined by the HTC Vive Controllers which are velocroed to the handlebars of the bike (Velcro allows for easy removal of the controllers). The X, Y, and Z coordinates of the two controllers are recorded when the handlebars are in the straight position, positioned for a right turn, and when positioned for a left turn. As the participant moves the handlebars, this is translated to a certain degree of turning in the VR environment. This translation was adjusted during pilot testing, to make the steering in VR subtle enough that it does not initiate dizziness and motion sickness, but responsive enough that the cyclist feels they can control their actions in VR. Tweaking the steering to make it feel realistic, controllable, and avoid dizziness required judgment based on responses during the pilot study. The steering adjustment is particularly tricky because steering on a stationary bike is already quite different from real-world steering in that you cannot lean to turn as you do on a real-bike. This results in a learning curve for the user, which we want to make as intuitive and realistic as possible, resulting in a steering mechanism that felt realistic and did not induce significant motion sickness.

Braking, because it initiates a deceleration in forward motion, has the potential to prompt motion sickness if the movement is not what the user expects. Using the HTC Vive controller trigger as a brake is a novel methodology to accomplish the braking action in a bicycle simulator. However, much like our steering, the braking required fine-tuning to ensure it be as realistic as possible. As discussed in Chapter Five, the braking deceleration effect was reduced to allow it to function in harmony with the speed output and the physical flywheel on the bicycle. While having a brake that did not feel as strong as expected resulted in some negative feedback in terms of realism from the participants, we believe this was the best choice to avoid any jarring deceleration followed by acceleration, or motion sickness from decelerating too quickly. During experimentation, some participants reported that removing them from the VR environment before they had come to a complete stop using the brake resulted in motion sickness, thereafter, the experimental protocol was modified to require the participant to brake fully at the end of the experiment before they were removed from the VR environment. In this way we developed a braking mechanism, that did not induce significant motion sickness.

7.1.2. Benchmarking

The first key contribution of the benchmarking study is simply developing a benchmarking methodology to address the lack of benchmarking or validation studies in the existing literature. There exists one study by O'Hern et al. which compares cyclist behavior while using the simulator to their behavior on a real-world roadway. Our benchmarking study develops a validation methodology using easily obtained video-footage of a road, in the absence of instrumented-cyclists on a real road. This approach has the advantage of studying cyclists in an uncontrolled environment. Video footage collection also allows for the benchmarking of any roadway environment that can be recreated in VR, not just a roadway which is a controlled, experimental environment. Using the video footage benchmarking methodology, we were able to validate the speed of cyclists between the real-world Water Street corridor and the replicated VR Water Street corridor.

The use of the speed limit of the corridor to set a constant speed for all motor vehicles in the virtual environment was found to be inconsistent with real-world traffic conditions. We propose that alternative methods for modeling traffic be considered if the intent is to recreate real-world conditions. Real-world speeds rather than speed limits could be measured and used. Average real-world speeds could be set speed for all motor vehicles, or a distribution of real-world speeds could be used.

Another method to determine realism of the bicycle simulator was developed using survey questions. Likert scale questions about realism of the bicycle simulator components were given to the participants after the study. This allowed us to determine impressions of realism generally and about certain components including steering, speed, braking, and acceleration. This method allowed us to determine that most components were perceived as realistic (speed, steering, traffic, scale, immersiveness, consistency with real-world experiences). It also revealed that the braking and acceleration components were perceived as less realistic. As previously discussed, this is related to how the braking mechanism interacts with the other elements of the simulator, particularly the flywheel in the Wahoo Kickr.

7.1.3 Infrastructure and perceived safety

One key contribution of the infrastructure and perceived safety study is developing a methodology for studying and comparing cyclist behavior in different roadway environments. This study was formatted as a within-subject study for the roadway environments (every participant cycled through all three roadway environments) and a between-subject study for the traffic volume (one group experienced low volume traffic and one group experienced high volume traffic).

The study also incorporated the use of survey data to assess cyclists' perceptions of the VR environments. Surveys for studying perceived safety are a well-established tool. Using them in combination with VR allows for comparison between survey results and behavior results from the simulator outputs.

The bicycle simulator output data allowed for the analysis of novel data-sources. In this study, speed, spatial positioning, braking frequency and location, and acceleration were all analyzed. These are all elements that are challenging to observe in a real-world environment.

Meaningful results from the study include: feelings of perceived safety were higher in the protected bike lane and bike lane compared to the as-built environment; speeds were significantly different in the three different environments; braking values were higher in the protected bike lane environment than in the bike lane environment; standard deviations of distance to the curb were smaller in the bike lane and protected bike lane environments than in the as-built environment.

7.2 LIMITATIONS

7.2.1 Simulator Development

The use of VR for studying cyclists presents an opportunity for innovative research, however, as with any methodology there are advantages drawbacks, and lessons learned. As described above in section 7.1.1 in terms of the physical simulator, the trigger braking mechanism does not feel like a typical bicycle brake and it does not affect a strong deceleration force. Future simulator development should improve on the bicycle brake realism while maintaining minimal motion sickness. Additionally, due to the need to keep resistance consistent between participants, the participants are told to avoid changing gears. This restricts their ability to behave as they normally might on a real bike.

7.2.2 Benchmarking

With the benchmarking study, in-person testing meant that experiments are time-intensive. It is not possible to test people at the same scale and ease as with, for example, a survey. Each test requires one hour of in-person testing time for the participant as well as for the researchers who are present to run and guide the test. Additionally, because of COVID-19 precautions, disinfection time between participants was required. This led to a smaller sample size than would be possible with other methods in the same time frame. Another limitation of the participant pool is the willingness of people's participation in an in-person experiment during the COVID-19 pandemic. We may discover that those willing to take on an additional risk to their health by coming to a lab in-person are those who perceive they are less likely to be severely impacted by the virus (younger, healthier) or those that are less risk averse. In additional to limitations with the participant pool, there are limitations associated with the design choices of the bicycle simulator and VR environment which impact the perceived realism. For example, the design choice concerning vehicle traffic in the environment was intended to keep the traffic pattern simple, this reflects our design abilities and the need for the environment to run smoothly and consistently. Motor vehicles follow a straight line along the road, they do not move over for bicyclists, and there are no motor vehicles approaching from side streets. The lack of variation in motor vehicle behavior may have affected how participants interpreted the perception of risk from traffic. Additionally, the VR environment contains no other pedestrians, cyclists, or other road users. The motor vehicles are the only moving feature in the environment. In reality, the corridor is highly trafficked by non-motorized users, which may increase bicycling stress.

The benchmarking study also contains some limitations related to the video footage collection. This creates limitation with regards to this step in the methodology. The low quality footage limited data collection to the type of road user (motor vehicle, cyclist, scooterist, pedestrian), interactions between road users, timestamps, and locations. More information about road users and their behaviors could not be discerned. Additionally, a larger dataset could not be created because the video footage was coded manually rather than using automated methods. Future validation work involving video footage should ensure high resolution data is captured.

7.2.3 Infrastructure and perceived safety

The same experimental constraints for the benchmarking study apply to the infrastructure and perceived safety experiment. This includes the participant pool limitations and the bicycle simulator limitations (the traffic environment, lack of other road users, braking, and gears).

7.3 FUTURE WORK

7.3.1 Future of Bicycle Simulation

Bicycle simulation will continue to grow as a field because of the advantages of simulation, as discussed in chapter two. Particularly by incorporating VR, simulation builds upon other research methodologies by offering easily modifiable virtual environments, controlled experiments, and an immersive experience for the user. As the field grows, there will continue to be significant changes as we have seen in recent years as technological advances have impacted the field. These advances will undoubtedly continue to make bicycle simulation an easier and more effective tool for studying cyclist behaviors in varied environments. HMDs have improved in their capacity to provide data just during the span of this dissertation research. After establishing the ORCL and before starting experiments, HTC Vive released their headset with eye-tracking capabilities. These new technologies will continue to iterate, improving ease of use, and data collection. HMD displays will continue to be thrive as a research tool because they are capable of providing an incredible immersive visual experience, increasing realism for the user compared to other visualization methods. Another example of sensing technology in our simulator is the use of smartwatches, which have advanced such that accurate smartwatch technology is extremely accessible. This enables time stamped sensing of elements like heartrate, galvanic skin response, and hand movements. This sensing data as well as the readily collected data from the bicycle simulator (lane position, driver behavior, interactions between cyclists and drivers, speed, braking, etc.) are novel datasets for studying bicycle safety and behavior. This expands the boundaries of what is possible in bicycle research.

Simulation, because it is a safe environment, allows for the incorporation of more diverse cycling populations. Real-world data which captures current cyclists only represents populations which already bike. Those that do not bike regularly, or at all may have different cycling needs; Less proficient cyclists or children may desire more separation from cars. Highly proficient road cyclists may prefer integration with cars (protected lanes or shared paths limit their speed) and would rather a focus on driver education and improved driving behavior in response to cyclists. Both populations must be considered in bicycle infrastructure design in order to reflect all cyclists' needs. Using simulation for cyclist data allows us to capture people who rarely or never cycle, and if our goal is to encourage cycling as a mode of transportation (for health, the environment, and for safety), understanding the needs of people who choose *not* to cycle is just as important as those who are already cycling.

7.3.2 Applications of Bicycle Simulation

There are a number of uses for the type of technology developed in this work. One example is for education. Pedestrian simulators have been used previously to teach safe street crossing behaviors, bicycle simulators could be used in a similar manor to teach children the rules of the road, how to interact with motor vehicles, safe positioning in the roadway or in bicycle infrastructure, and more complex behaviors such as navigating intersections, or intersections with bicycle signals. Another space for bicycle simulation is in new technology acceptance. There are some types of bicycle infrastructure (advisory bike lanes, bicycle traffic signals) which are not as commonplace as regular bike lanes or protected bike lanes. Simulation could bring more awareness to these types of infrastructure and help communities be more willing to accept innovative roadway design solutions. This is related to another application of bicycle simulation which has been previously discussed, public outreach. VR can be a tool to garner public feedback on proposed transportation projects, helping the public to fully experience proposed corridor or intersection redesign. In this way, bicycle simulation can have a meaningful impact as a research tool and as a real-world application.

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PUBLICATIONS & PRESENTATIONS

PUBLICATIONS

Guo, X., **E. Robartes**, A. Angulo, T.D. Chen, and A. Heydarian. (July 2021). "Benchmarking the Use of Immersive Virtual Bike Simulators for Understanding Cyclist Behaviors." https://doi.org/10.31224/osf.io/mrxgh

Robartes, E., E. Chen, T.D. Chen, P. Ohlms. "Assessment of Local, State, and Federal Barriers to Implementing Bicycle Infrastructure: A Virginia Case Study." Case Studies on Transport Policy. 2021. https://doi.org/10.1016/j.cstp.2021.02.004

Robartes, E., and T.D. Chen. "Crash histories, safety perceptions, and attitudes among Virginia bicyclists." Journal of Safety Research 67: 189-196, 2018.

Robartes, E. and T. D. Chen. "The Effect of Crash Characteristics on Cyclist Injuries: An Analysis of Virginia Automobile-Bicycle Crash Data." Accident Analysis & Prevention 104: 165-173, 2017.

CONFERENCE AND SYMPOSIUM PRESENTATIONS

*Underlined name is the presenter

Robartes, E., X. Guo, A. Angulo, T.D. Chen, A. Heydarian. (2021). "Evaluating Bicycle Infrastructure Through Perceived Safety: A Virtual Reality Simulation Experiment." Paper to be presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E., A. Angulo, X. Guo, T.D. Chen, A. Heydarian. (2021). "Benchmarking a Virtual Reality Bicycle Simulator for Transportation Research." Paper to be presented at the Transportation Research Board Annual Meeting, Washington, DC.

Angulo, A., **E. Robartes**, X. Guo, T.D. Chen, A. Heydarian, B. Smith. (2022). "Evaluating Current and Future Mid-Block Crossing Safety Treatments Using Virtual Reality Simulation". Paper to be presented at the Transportation Research Board Annual Meeting, Washington, DC.

Angulo, A., **E. Robartes**, X. Guo, T.D. Chen, A. Heydarian, B. Smith. (2022). "Validation of a Virtual Reality Simulator with Real-World Observations for Pedestrian Safety at Midblock Crossings". Paper to be presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E., A. Angulo, X. Guo, T.D. Chen, A. Heydarian. (2021). "Validation of a Bicycle Simulator in Virtual Reality for the Study of Bicyclists' Perceived Safety" Paper to be presented at the International Cycling Safety Conference, Virtual.

Guo, X., **Robartes, E**. M., Angulo, A., Chen, T. D., Heydarian, A, (2021) "Benchmarking the Use of Immersive Virtual Bike Simulators for Understanding Cyclist Behaviors.," ASCE 2021 International Conference on Computing in Civil Engineering, Orlando, Florida.

Robartes, E., A. Angulo, X. Guo, T.D. Chen, A. Heydarian. (2021). "Benchmarking a Virtual Reality Bicycle Simulator for Transportation Research." Presented at The Transportation Research Board Conference on Advancing Transportation Equity, Virtual.

Robartes, E., A. Angulo, T.D. Chen. (2021) “Benchmarking Virtual Reality Bicycle and Pedestrian Simulators for Transportation Research.” Poster presented at the ASCE International Conference on Transportation & Development, Virtual.

Guo, X., A. Angulo, **E. Robartes**, T.D. Chen, A. Heydarian. (2021). “Assessing and Improving Cyclists' Situational Awareness and Safety through Physiological Sensing and Augmented Reality Technology" Presented at the Transportation Research Board Annual Meeting, Virtual.

Angulo, A., **E. Robartes**, X. Guo, T.D. Chen, A. Heydarian. (2021). "Development of Virtual Reality Simulators to Assess Perceived Safety of Vulnerable Road Users" Committee on Transportation Visualization at the Transportation Research Board Annual Meeting, Virtual.

Angulo, A., **E. Robartes**, T.D. Chen, M.D, Dean, E. Chen, A. Heydarian, B.L. Smith. (2020). “The Use of Virtual Reality Simulators in Bicycle and Pedestrian Human Subject Testing: A Synthesis” Paper presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E. and T.D. Chen. (2019) “Assessing Bicyclists’ Perceived Safety, Risk, and Comfort – State of the Literature” Paper presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E., E. Chen, T.D. Chen, P. Ohlms. (2019) “Assessment of Local, State, and Federal Barriers to Implementing Bicycle Infrastructure: A Virginia Case Study” Paper presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E., E. Chen, T.D. Chen, P. Ohlms. (2018) “Assessment of Local, State, and Federal Barriers to Implementing Bicycle Infrastructure: A Virginia Case Study” Paper presented at the International Cycling Safety Conference, Barcelona, Spain.

Robartes, E., and T.D. Chen. (2018). “Crash Histories, Safety Perceptions, and Attitudes among Virginia Bicyclists” Paper presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E., and T.D. Chen. (2017). “Bicycle and Automobile Safety Perception Analysis” Presented at the International Cycling Safety Conference, Davis, CA.

Robartes, E. and T.D. Chen. (2017). “Virginia Automobile and Bicycle Crash Safety Analysis” Paper presented at the University of Virginia Civil and Environmental Engineering Graduate Research Symposium, Charlottesville, VA.

Robartes, E. and T.D. Chen. (2017). “Virginia Automobile and Bicycle Crash Safety Analysis” Paper presented at the Transportation Research Board Annual Meeting, Washington, DC.

Robartes, E. and T.D. Chen. (2016). “Virginia Automobile and Bicycle Crash Safety Analysis” Paper presented at the Pedestrian and Bicycle Safety UTC Spotlight Conference, Washington, DC.

Robartes, E. and T.D. Chen. (2016). “Virginia Automobile and Bicycle Crash Safety Analysis” Work presented at the Virginia Civil and Environmental Engineering Graduate Research Symposium, Charlottesville, VA.

INVITED TALKS

<u>Robartes, E.</u> and T.D. Chen. (2021). "Virginia Bicycle Datasets" Invited talk at the Thomas Jefferson Planning District Commission MPO Technical Committee, Virtual.

<u>Robartes, E.</u> (2019). "Autonomous Vehicle Interactions with Vulnerable Road Users" Invited talk at the Richmond Active Transportation Work Group Meeting, Richmond, VA.

CHAPTER EIGHT: APPENDICES

APPENDIX A: RECRUITMENT MATERIALS

Invitation Email:

Dear **NAME**,

Thank you for your interest in a bicycle and pedestrian virtual reality (VR) research study with the Omni-Reality and Cognition Lab (ORCL). If you would like to participate, you can **sign up for a time slot at this link.** || We have scheduled you for a time slot on **DATE at TIME**.

Please complete the following consent form prior to arriving for the research study consent form. Additionally, please provide me with a phone number I can use to call you to administer a very brief health screening before the experiment.

You will complete several surveys during the research study, your participant number is **XXX**. (you will use this number during the research study to anonymize the data)

Upon agreeing to participate, the following types of information will be collected:

Environmental Sensors:

- Virtual Reality (VR) recording – a recording of your field of view in VR and an external recording of the lab setup will be collected during the experiment

Human Sensing

- VR headset – the VR headset will be collecting information regarding your movements and interactions with items in the virtual environment
- Heart rate, acceleration, and arm/hand movement – collected through a smartwatch
- Bicycle trainer – our state of the art bicycle trainer will be collecting speed, acceleration, and turning movements within the virtual reality environments. You will experience feedback such as variable wind speeds based on your speed and elevation angle control when you are going up or downhill in VR.

You have permission to review your data before giving them to our researchers. At any time if you have an issue with any information shared, you can request for your data to be deleted and we will remove it from our database. Additionally, you are free to withdraw from the study at any time you wish.

Please note: You must be 18 or older to participate in this study. Participants with colorblindness cannot participate in this study due to the nature of the virtual reality equipment. Furthermore, if you wear glasses, we highly recommend that you wear contacts if you wish to participate in the study, as those with glasses often have trouble wearing the headset comfortably. We apologize for any inconvenience.

We recommend you wear clothes you feel comfortable riding a bike in, as well as something with a pocket or belt loop (the VR headset has a battery pack that you have to hook on to yourself).

University COVID-19 protocols are being strictly followed in this laboratory. All equipment will be sanitized prior to your use of it, and hand sanitizer and gloves will be available. Masks are required at all times in the lab. Please do not participate if you have any symptoms of COVID-19. We will give you a brief health screening upon your arrival on grounds. All researchers are participating in weekly COVID testing and daily health screenings.

The experiment will take approximately one hour to complete and you will receive a $15 gift card for your time. Attached is a map of grounds to help you locate the ORCL in Thornton Hall. Or if you prefer, the GPS coordinates are: 38.032545, -78.510594

If you are interested in getting more information about the study or have any concerns or questions, please respond to this email or contact us at orcl@virginia.edu.

Donna Chen
Arsalan Heydarian
Erin Robartes
Austin Angulo
Xiang Guo

Follow Up Email:
Dear **NAME**

This is a reminder of your appointment at the Omni-Reality and Cognition Lab for the bicycle and pedestrian virtual reality experiment at **TIME on DAY.**

Please remember to complete the **consent form** before your arrival in the lab.

We look forward to seeing you tomorrow.

Donna Chen
Arsalan Heydarian
Erin Robartes
Austin Angulo
Xiang Guo

APPENDIX B: CONSENT FORM

Please read this consent agreement carefully before you decide to participate in the study.

Purpose of the research study: The purpose of this research is to test the effectiveness of Virtual Reality (VR) as a tool to replicate bicyclist and pedestrian environmental settings. In this experiment, we aim to increase understanding of perceived safety and technological acceptance as it relates to bicyclists, pedestrians, and the road environment. This information can be used by planners and engineers to better design technology and safe infrastructure for bicyclists and pedestrians. With VR, we can study human behaviors in settings/scenarios that (1) we have limited or no access to (e.g., design of a new intersection that has not been built yet) or (2) are considered high-risk environments for collecting real-life data.

What you will do in the study: You will participate in a pedestrian and a bicyclist study.

In the **Pedestrian** Study, you will be placed in an environment in which you can naturally interact with vehicles. In this study, you will be asked to wear physiological sensing and VR equipment. You will be placed in multiple virtual environments, each different from one another, and will be asked to perform actions such as "cross the road when you feel safe". You will be given a short questionnaire after each test in which you will respond to your thoughts and feelings regarding your experience.

In the **Bicyclist** Study, you will be placed in an environment in which you can naturally interact with vehicles. You will be seated on a stationary bike and will be wearing a VR headset and physiological sensing equipment. The instrumented bicycle will allow your actions to be replicated in the virtual environment (speeding up, slowing down, steering). You will be given a short questionnaire after each test in which you will respond to your thoughts and feelings regarding your experience.

Time required: The study will require about 1 hour of your time.

Risks: Subjects who wear glasses may be excluded from this study if the VR headset cannot fit properly over the glasses. The physical components of these tasks are not stressful, and include head and body turning, moving, and pointing. Light and sound intensities are well within normal ranges. The only foreseeable physical risks are potential eye strain, dizziness, and mild nausea. There are no known mental risks. You will be asked to remove the head mounted display if you experience any significant eye strain, dizziness, or nausea during the sessions. You will be given rest breaks in between the sessions. At any time during the experiment, you may stop the experiment if you feel uncomfortable or cannot continue due to any reason.

Benefits: There are no direct benefits to you associated with your participation in this study. The proposed experiments are straightforward tests of performance and visual comfort using standard virtual environment displays and trackers.

Confidentiality: The information that you give in the study will be handled confidentially. Your information will be assigned a code number. The list connecting your email to this code will be kept in a locked file. When the study is completed and the data have been analyzed, this list will be deleted. Your name will not be used in any report. Once any data is deleted from a request, the changes will propagate correspondingly to the backup drives.

The experimental data collected does not contain individually identifiable information. Thus, a loss of confidentiality would not put you at risk, and the researchers will use caution in handling the data.

Voluntary participation: Your participation in the study is completely voluntary.

Right to withdraw from the study: You have the right to withdraw from the study at any time without penalty.

How to withdraw from the study: If you want to withdraw from the study, please contact the ORCL lab at orcl@virginia.edu indicating that you would like to withdraw from the study. There is no penalty for withdrawing. You may request that your archived data be destroyed upon withdrawing from the study.

Payment: You will receive a $15 gift card as payment for participating in the study.

If you have questions about the study, contact:

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Refer to IRB-SBS Protocol #2148

You will receive a copy of this form for your records.

APPENDIX C: QUESTIONNAIRES

Pre-Experiment Questionnaire

ORCL Pedestrian and Bicycle VR Pre-Experiment Questionnaire

Omni-Reality and Cognition Lab (ORCL) Pedestrian and Bicycle VR Pre-Experiment Questionnaire

Thank you for your interest in participating in this ORCL virtual reality experiment at UVA. The following questions will ask about you and your transportation habits.

Please provide the participant number given to you in your experiment confirmation email __________

How did you hear about this study?

- O Word of mouth
- O An email
- O A flyer
- O Social media
- O Other ____

Questions about your Transportation Habits
In the past week, have you _______ (please check all that apply)

- ☐ Walked to a destination or walked for recreation/exercise?
- ☐ Ridden a bike?
- ☐ Taken transit?
- ☐ Driven or ridden in an automobile?
- ☐ None of the above

Approximately how many miles did you walk last week? _______________________________
Approximately how many miles did you bike last week? _______________________________
Approximately how many miles did you travel by transit last week?____________________________
Approximately how many miles did you travel by automobile last week?________________________

What describes your attitude toward biking?

- "Strong and Fearless" - I will ride anywhere, no matter the facilities provided
- "Enthused and Confident" -I like to ride and will do so with dedicated infrastructure
- "Interested but Concerned" - I like the idea of riding but have concerns
- "No way, no how" - I do not ride a bike

Questions about your experience with different technologies
Do you have any experience with virtual reality headsets?

- I have never heard of them
- I have heard of them but never seen one
- I have some knowledge about them and have seen them for sale
- I don't own one but I have used one before
- I own one and use it sometimes
- I own one and use it regularly

Questions about your personality
Here are a number of personality traits that may or may not apply to you. Please indicate the extent to which you agree or disagree with that statement. You should rate the extent to which the pair of traits applies to you, even if one characteristic applies more strongly than the other.

	Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree
Extraverted, enthusiastic							
Critical, quarrelsome							
Dependable, self-disciplined							
Anxious, easily upset							
Open to new experiences, complex							
Reserved, quiet							
Sympathetic, warm							
Disorganized, careless							
Calm, emotionally stable							
Conventional, uncreative							

Socio-demographic Questions
The following questions ask you about the amount of time you devote to different activities each day.

	Hours	Minutes
On average, how many hours of physical activity do you have each day?		
On average how many hours a day do you use a smartphone?		

On average how many hours do you spend outdoors each day?		

Do you have any visual impairments?
- O Yes - please explain here ____
- O No

Are you color blind?
- O Yes
- O No
- O Not Sure

What is your current employment status?

O Employed full-time O Self-employed O Working part time O Unemployed O Retired	O Student O Stay at home spouse O On sabbatical O Other ____________________

What is the highest educational degree you have earned?

O Less than high school diploma O High school/GED O Some college (no degree)	O Associates degree O Bachelor's degree O Graduate degree

Do you live in a college dormitory or with roommates?
- O Yes
- O No

What is your annual household income?

O $0-$10,000 O $10,001-$15,000 O $15,001-$25,000 O $25,001-$35,000 O $35,001-$50,000	O $50,001-$75,000 O $75,001-$100,000 O $100,001-$200,000 O $200,000+ O Prefer not to answer

How many of the following does your household have?
- O Bicycles ____
- O Electric bicycles ____
- O Mopeds or motorcycles ____
- O Passenger cars, vans, SUVs, pickup trucks ___________________________________
- O Motor homes, recreational vehicles, buses, or large trucks _________________________

What is your marital status?
- O Single
- O Married

- ○ Widowed
- ○ Divorced
- ○ Separated

Do you have children (under the age of 18)?

- ○ No
- ○ Yes

How many children do you have?

▼ 1 ... More than 10

Please complete the following question for each child:

	What is the age of your child?	Does your child live with you?	
	Answer 1	Yes	No
Child 1			
…..			
Child 10			

What is your gender?

- ○ Female
- ○ Male
- ○ Other ____

What is your age? ____

Would you describe yourself as... (Please check all that apply)

- ☐ American Indian/Native American
- ☐ Asian/Pacific Islander
- ☐ Black/African American
- ☐ Hispanic/Latino
- ☐ White/Caucasian
- ☐ Other ____
- ☐ Prefer not to answer

Post-Experiment Questionnaire

ORCL Bicyclist VR Post-Experiment Questionnaire

Thank you for your participation in the virtual reality simulator bicycle experiment. The following questions will ask you about your experience in the virtual environment.

Please provide the participant number given to you in your experiment confirmation email:____________

Did you experience any motion sickness while using the bicycle simulator?
- ○ Yes
- ○ No

Did you need to stop the experiment due to motion sickness?
- ○ Yes
- ○ No

Questions about the realism of the virtual environment:
How aware were you of events occurring in the real world around you while performing the assigned tasks in the virtual environment?

	Not at all aware (1)	(2)	Somewhat aware (3)	(4)	Very aware (5)

How responsive was the environment to actions that you performed?

	Not responsive at all (1)	(2)	Somewhat responsive (3)	(4)	Very responsive (5)

How immersed were you in the virtual environment experience?

	Not immersed at all (1)	(2)	Somewhat immersed (3)	(4)	Very immersed (5)

Did the virtual environment feel appropriately to scale?

	Not at all to scale (1)	(2)	Somewhat to scale (3)	(4)	Yes, appropriate scaled (5)

To what extent did your experiences in the virtual environment seem consistent with your real-world experiences as a bicyclist?

	Not at all consistent (1)	(2)	Somewhat consistent (3)	(4)	Very consistent (5)	N/A I do not bike in the real world.

Questions about the realism of your movements as a bicyclist
The following questions ask how realistic various bicycle movements were in the simulator.

	Not realistic at all (1)	(2)	Somewhat realistic (3)	(4)	Very realistic (5)
Bicycle Speed					
Bicycle Acceleration					

The following questions ask how realistic various bicycle movements were in the simulator.

	Not realistic at all (1)	(2)	Somewhat realistic (3)	(4)	Very realistic (5)	N/A (I did not try braking/steering in the simulator)
Bicycle Braking						
Bicycle Steering						

How distracting was the control mechanism (the remote control) device that you used in order to brake?

	Very distracting (1)	(2)	Somewhat distracting (3)	(4)	Not distracting at all (5)	N/A (I did not try braking in the simulator)

Questions about the traffic in the virtual environment:
How realistic was the vehicle traffic in the virtual environment?

	Not realistic at all (1)	(2)	Somewhat realistic (3)	(4)	Very realistic (5)

Do you feel more or less compelled to observe the "rules of the road" while bicycling in the virtual environment compared to bicycling in real life?

	Less compelled (1)	(2)	No change compared to real life (3)	(4)	More compelled (5)

Questions about your perceived safety:
How realistic was your sense of risk in the virtual environment?

	Not realistic at all (1)	(2)	Somewhat realistic (3)	(4)	Very realistic (5)

How safe did you feel in the following situations?

	Not safe at all (1)	(2)	Somewhat safe (3)	(4)	Very safe (5)
Biking in the road with no bike infrastructure					
Biking in the bike lane					
Biking in the protected bike lane with pylons					

How safe did you feel concerning the cars driving past you

	Not safe at all (1)	(2)	Somewhat safe (3)	(4)	Very safe (5)
while biking in the road with no bike infrastructure					

while biking in the bike lane	
while biking in the protected bike lane with pylons	

The three bicycling environments you experienced are listed below. Please select the one in which you felt the LEAST SAFE and the one in which you felt the SAFEST.

LEAST SAFE		SAFEST
○	Bicycling in the road with no bike infrastructure	○
○	Bicycling in an unprotected bike lane (striping on road designating bike lane)	○
○	Bicycling in a protected bike lane (striping on road and pylons designating bike lane)	○

Do you have any additional comments?

____

Thank you for your participation in the experiment! The next arrow will submit the survey.

APPENDIX D: TEST SCRIPT

Test Overview Script

Physiological Data Collection

Start the recording app on the smartwatch (top right button, swear app, start).

Hand smartwatch to the participant for them to put on their wrist so that we can start collecting baseline data while explaining the experiments.

Welcome

Welcome to the Omni-Reality and Cognition Laboratory and thank you for this participation in this study. Today, you will be entering a virtual environment modeled after the Water Street corridor parallel to the downtown mall in Charlottesville, VA as both a pedestrian and a bicyclist. As a pedestrian you will be crossing the street, and as a bicyclist you will be biking down the road.

During this experiment, you will be wearing a virtual reality headset equipped with eye tracking technology, and handheld controllers. Before we begin both the bicycle and pedestrian experiments, you will be placed in the virtual environment so that you can familiarize yourself with the controls. Video recording of your actions will be recorded in the virtual environment (what you are seeing) as well as in the testing room (*point at cameras set up in room).

Should you have any questions or concerns during the test please feel free to ask me at any time. Should you experience any motion sickness and wish to exit the virtual environment, please let me know at any moment. Once the first test is complete I will ask you to remove the headset and you will take a survey on this laptop (*point out laptop). Once that is complete, we will advance to the next part of the experiment, afterwards, you will fill out one more survey and be paid for your time here.

All data from this test will be made public, however, none of the data collected will in any way, shape, or form, identify you as having been a test subject. Do you have any questions for me before we begin?

Start by having the participant complete the pre-experiment questionnaire:
https://virginia.az1.qualtrics.com/jfe/form/SV_9Lyzpxh1ojcL0Pz

Pedestrian Script

Familiarization

Use a spare headset to demonstrate:

Show the participant the knob on the back which adjusts the width of the headset and the knob on the front right which adjusts for the distance between your eyes for focus.

Show the participant relevant touchpad information, use the controller

Explain blue grid, stay inside, if you walk outside you might walk into a wall.

Start by facing in the direction of the arrow on the ground. Clip the battery pack to yourself, and then put on the HTC VIVE headset and make any adjustments so that it fits snug on your head. There is a strap on the top of the headset that adjusts the height that the headset sits on your head and a knob on the back of the headset that adjusts the width of the headset.

Pick up the controllers at your feet. On the bottom of each virtual controller you will see a hand logo indicating which hand each controller represents, please be sure that the hand with the thumb on the right side of the hand is in your left hand and that the controller with the thumb on the left side of the hand is in your right hand.

Eye Tracking
Next, I will guide you through the eye tracking process. Look at the controller in your right hand, there is a button located at the bottom of the controller with a square on it. Press this button and a window will appear in front of you. On that window, in the bottom panel, there is a blue symbol of an eye; with your controller, point the laser pointer at this symbol and pull the trigger on the back of the controller. If there is no laser emitting from your right controller, pull the trigger on the back of the controller first. Hit calibrate and follow the instructions.

Once the virtual environment has been loaded…

In order to move forwards, you walk forwards. You may change the direction you are walking by changing direction or turning around, but do note that the space you can walk in is limited and shown by a light blue grid that appears when you are near the edge of the space you can walk in. The virtual space is designed to be contained within the space of this room so that you do not walk into any objects or walls. Walk around for a bit to familiarize yourself with the environment.

Spend as much time as you wish becoming familiar with the environment, when you are ready to move forward, let me know.

Experiments
The order of these will be randomized

Experiment 1 - As Built
You will now be placed within the (first/second/third) of three environments. Your task is to cross the road when you are ready. Wait for one car to drive by before you begin crossing.

Experiment 2 - Rapid Flashing Beacon
You will now be placed within the (first/second/third) of three environments.There is a rapid flashing beacon with a functional button which you can use to cross the road if you wish. Push the controller into the button, you will see it press down and that means you have pressed it. Your task is to cross the road when you are ready, wait for one car to drive by before you do anything in the environment.

Experiment 3 - Phone Application
You will now be placed within the (first/second/third) of three environments. In this environment, you will have a cell phone in your right hand equipped with a cell phone app that allows you to send a message to approaching vehicles of your intent to cross the road. The ability to send this warning message is restricted to the vicinity of the midblock crosswalk, you will know that you are able to send this message when the phone screen asks you if you'd like to cross the road. Your task is to cross the road in the manner you wish, wait for the first car to drive by before you do anything in the environment.

Debrief

You may now remove the headset and place it on the designated spot on the ground with your controllers. Experimentation within the virtual environment is now complete. During this test, we monitored your crossing behavior at the Water Street corridor and how that behavior changed with alternative technologies.

Post-Test

Now that you have finished the VR phase of the experiment, we ask that you fill out the survey on this computer. https://virginia.az1.qualtrics.com/jfe/form/SV_dotA6XNUr2eoUuN

If the bicycle experiment has also been finished:

Once you have finished, let me know and I will pay you for your time. *Once complete, pay test subjects for their time.*

Bicyclist Script

Bicycle Adjustments (before using VR headset)

- Adjust bicycle seat height (should be about belt high)
- Have the participant get on the bike and practice pedaling, turning, and braking before putting on a headset.
- Explain that the trigger on the right controller is the brake and that both of the controllers are used to control steering.

Familiarization

Use a spare headset to demonstrate:

Show the participant the knob on the back which adjusts the width of the headset and the knob on the front right which adjusts for the distance between your eyes for focus.

Start by getting on the bike. Clip the battery pack to yourself, and then put on the HTC VIVE headset and make any adjustments so that it fits snug on your head. There is a strap on the top of the headset that adjusts the height that the headset sits on your head and a knob on the back of the headset that adjusts the width of the headset.

Look at the controllers on the handlebars, check that the right and left hands are in the correct location. Once you are comfortable we will calibrate the eye tracking. You will have to use the right controller to set it up (slide out of velcro) and then I will assist you in reattaching it to the handlebars.

Eye Tracking
Next, I will guide you through the eye tracking process. Look at the controller in your right hand, there is a button located on the bottom of the front of the controller with a square on it. Press this button and a window will appear in front of you. On that window, in the bottom panel, there is a blue symbol of an eye; with your controller, point the laser pointer at this symbol and pull the trigger on the back of the controller. If there is no laser emitting from your right controller, pull the trigger on the back of the controller first. Hit calibrate and follow the instructions.

If controllers have turned off, turn the right one on first and then the left, they tend to connect in this order.

We will now place you in the familiarization environment, don't start pedaling yet, we will first calibrate the steering.

Initiate familiarization environment. Once the virtual environment has been loaded…

Calibrate steering: Turn handlebars all the way to the right (click to calibrate highest), position handlebars perfectly straight (click to calibrate middle), and to the left (click to calibrate lowest).

In order to move forwards, simply pedal. The bike takes a minute to start moving, so just be prepared for that, it has a little lag. You may change the direction you are cycling by steering as you normally would. You may try this now. You may also brake on the bike by pulling the trigger on the right hand. You may try this now.

To start up again, simply let go of the trigger and pedal. As long as the trigger is pulled you will slow down to a halt.

Take as much time as you would like to familiarize yourself with the environment. When you feel that you are ready to move forward, let me know.

Experiment

The order of these experiments will be randomized.

Base Case

You will now be placed in the (first/second/third) of three environments. Your task is to bike to the second traffic signal at the end of the corridor. Do not start pedaling when you first enter the environment, we will first calibrate the steering.

Bike Lane

You will now be placed in (first/second/third) of the three environments. Your task is to bike to the traffic signal at the end of the corridor. Do not start pedaling when you first enter the environment, we will first calibrate the steering.

Protected Bike Lane

You will now be placed in the (first/second/third) of the three environments. Your task is to bike to the traffic signal at the end of the corridor. Do not start pedaling when you first enter the environment, we will first calibrate the steering.

Debrief

You may now remove the headset and place it on the designated spot on the ground with your controllers. Experimentation within the virtual environment is now complete. During this test, we monitored your cycling behavior along Water Street and how that behavior changed with alternative designs.

Post-Test

Now that you have finished the VR phase of the experiment, we ask that you fill out the survey on this computer. https://virginia.az1.qualtrics.com/jfe/form/SV_9NxShM5CxUBUhsp

If the pedestrian experiment has also been completed:
Once you have finished, let me know and I will pay you for your time. *Once complete, pay test subjects for their time.*

APPENDIX E. BENCHMARKING ANALYSIS

5.4.2 Speed Analysis

```
	Welch Two Sample t-test

data:  AvgS4 and VFSpeed
t = 1.3173, df = 70.757, p-value = 0.192
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -0.4289715  2.0990797
sample estimates:
mean of x mean of y
 14.99639  14.16133
```

APPENDIX F. BICYCLE INFRASTRUCTURE AND PERCEIVED SAFETY ANALYSIS

6.4 SURVEY RESULTS

6.4.1 Stated Preference Surveys: "How safe did you feel using the different kinds of bike infrastructure?"

Within Subject Effects

Repeated Measures ANOVA of perceived safety question responses

Descriptive Statistics

	Mean	Std. Deviation	N
AsBuilt	2.60	1.195	50
BikeLane	3.90	.763	50
ProtectedBikeLane	4.12	1.100	50

Mauchly's Test of Sphericity[a]

Measure: Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.547	28.980	2	.000	.688	.701	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	67.480	2	33.740	29.918	.000	.379
	Greenhouse-Geisser	67.480	1.376	49.032	29.918	.000	.379
	Huynh-Feldt	67.480	1.403	48.100	29.918	.000	.379
	Lower-bound	67.480	1.000	67.480	29.918	.000	.379
Error (Environments)	Sphericity Assumed	110.520	98	1.128			
	Greenhouse-Geisser	110.520	67.436	1.639			
	Huynh-Feldt	110.520	68.743	1.608			
	Lower-bound	110.520	49.000	2.256			

Pairwise Comparisons

Measure: Safety

(I) Environments	(J) Environments	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-1.300*	.165	.000	-1.708	-.892
	3	-1.520*	.274	.000	-2.200	-.840
2	1	1.300*	.165	.000	.892	1.708
	3	-.220	.181	.693	-.670	.230
3	1	1.520*	.274	.000	.840	2.200
	2	.220	.181	.693	-.230	.670

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

High and Low Vehicle Volume Effects

Repeated Measures ANOVA of perceived safety question responses with traffic volume as between-subject effect.

Within-Subjects Factors

Measure: Perceived_Safety

Environments	Dependent Variable
1	AsBuilt_A
2	BikeLane_A
3	ProtectedBikeLane_A

Descriptive Statistics

	HighLow	Mean	Std. Deviation	N
As-Built	High	2.50	1.140	26
	Low	2.71	1.268	24
	Total	2.60	1.195	50
Bike Lane	High	4.00	.800	26
	Low	3.79	.721	24
	Total	3.90	.763	50
Protected Bike Lane	High	4.27	.827	26
	Low	3.96	1.334	24
	Total	4.12	1.100	50

Mauchly's Test of Sphericity[a]

Measure: Perceived_Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt	Epsilon[b] Lower-bound
Environments	.547	28.315	2	.000	.688	.717	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + HighLow
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Sphericity not assumed, use Greenhouse-Geisser.

Tests of Within-Subjects Effects

Measure: Perceived_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	66.474	2	33.237	29.372	.000	.380
	Greenhouse-Geisser	66.474	1.377	48.278	29.372	.000	.380
	Huynh-Feldt	66.474	1.434	46.364	29.372	.000	.380

	Lower-bound	66.474	1.000	66.474	29.372	.000	.380
Environments * HighLow	Sphericity Assumed	1.888	2	.944	.834	.437	.017
	Greenhouse-Geisser	1.888	1.377	1.371	.834	.399	.017
	Huynh-Feldt	1.888	1.434	1.317	.834	.404	.017
	Lower-bound	1.888	1.000	1.888	.834	.366	.017
Error(Environments)	Sphericity Assumed	108.632	96	1.132			
	Greenhouse-Geisser	108.632	66.091	1.644			
	Huynh-Feldt	108.632	68.819	1.579			
	Lower-bound	108.632	48.000	2.263			

No significant effects between traffic volumes and perceived safety means in environments (p=0.399)

Repeated measures ANOVA tests of perceived safety question responses for each bicycling environment, for high and low volume samples.
High Volume

Descriptive Statistics

	Mean	Std. Deviation	N
HIGHAsBuilt	2.50	1.140	26
HIGHBikeLane	4.00	.800	26
HIGHProtectBikeLane	4.27	.827	26

Mauchly's Test of Sphericity[a]

Measure: Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt	Epsilon[b] Lower-bound
Environments	.738	7.291	2	.026	.792	.837	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	47.256	2	23.628	28.996	.000	.537
	Greenhouse-Geisser	47.256	1.585	29.819	28.996	.000	.537
	Huynh-Feldt	47.256	1.674	28.224	28.996	.000	.537
	Lower-bound	47.256	1.000	47.256	28.996	.000	.537

Error(Environments)	Sphericity Assumed	40.744	50	.815			
	Greenhouse-Geisser	40.744	39.620	1.028			
	Huynh-Feldt	40.744	41.858	.973			
	Lower-bound	40.744	25.000	1.630			

Pairwise Comparisons

Measure: Safety

(I) Environments	(J) Environments	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-1.500*	.186	.000	-1.977	-1.023
	3	-1.769*	.300	.000	-2.540	-.999
2	1	1.500*	.186	.000	1.023	1.977
	3	-.269	.252	.884	-.915	.376
3	1	1.769*	.300	.000	.999	2.540
	2	.269	.252	.884	-.376	.915

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Low Volume

Descriptive Statistics

	Mean	Std. Deviation	N
LOWAsBuilt	2.7083	1.26763	24
LOWBikeLane	3.7917	.72106	24
LOWProtectBikeLane	3.9583	1.33447	24

Mauchly's Test of Sphericity[a]

Measure: Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.352	22.942	2	.000	.607	.623	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	22.111	2	11.056	7.491	.002	.246

	Greenhouse-Geisser	22.111	1.214	18.214	7.491	.008	.246
	Huynh-Feldt	22.111	1.245	17.753	7.491	.007	.246
	Lower-bound	22.111	1.000	22.111	7.491	.012	.246
Error(Environments)	Sphericity Assumed	67.889	46	1.476			
	Greenhouse-Geisser	67.889	27.920	2.432			
	Huynh-Feldt	67.889	28.646	2.370			
	Lower-bound	67.889	23.000	2.952			

Pairwise Comparisons

Measure: Safety

(I) Environments	(J) Environments	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-1.083*	.275	.002	-1.794	-.373
	3	-1.250*	.471	.043	-2.466	-.034
2	1	1.083*	.275	.002	.373	1.794
	3	-.167	.267	1.000	-.856	.523
3	1	1.250*	.471	.043	.034	2.466
	2	.167	.267	1.000	-.523	.856

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Gender Effects

Repeated Measures ANOVA of perceived safety question responses with gender as between-subject effect.

Descriptive Statistics

	Gender	Mean	Std. Deviation	N
As-Built	Female	2.17	.717	23
	Male	2.96	1.400	27
	Total	2.60	1.195	50
Bike Lane	Female	3.96	.767	23
	Male	3.85	.770	27
	Total	3.90	.763	50
Protected Bike Lane	Female	4.43	.945	23
	Male	3.85	1.167	27
	Total	4.12	1.100	50

Mauchly's Test of Sphericity[a]

Measure: Perceived_Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.580	25.592	2	.000	.704	.734	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.
a. Design: Intercept + Gender
Within Subjects Design: Environments
b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Sphericity cannot be assumed because $p < 0.05$. Use Greenhouse-Geisser correction.

Tests of Within-Subjects Effects

Measure: Perceived_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	71.567	2	35.783	34.884	.000	.421
	Greenhouse-Geisser	71.567	1.409	50.808	34.884	.000	.421
	Huynh-Feldt	71.567	1.469	48.728	34.884	.000	.421
	Lower-bound	71.567	1.000	71.567	34.884	.000	.421
Environments * Gender	Sphericity Assumed	12.047	2	6.023	5.872	.004	.109
	Greenhouse-Geisser	12.047	1.409	8.552	5.872	.010	.109
	Huynh-Feldt	12.047	1.469	8.202	5.872	.009	.109
	Lower-bound	12.047	1.000	12.047	5.872	.019	.109
Error(Environments)	Sphericity Assumed	98.473	96	1.026			
	Greenhouse-Geisser	98.473	67.612	1.456			
	Huynh-Feldt	98.473	70.498	1.397			
	Lower-bound	98.473	48.000	2.052			

The interaction effect between gender and the different environments is significant ($p=0.01$), so we should look at the environments separately with respect to gender.

Repeated measures ANOVA split by male/female. Factor is three different environments, measure is perceived safety

Descriptive Statistics

Gender		Mean	Std. Deviation	N
Female	As-Built	2.17	.717	23
	Bike Lane	3.96	.767	23
	Protected Bike Lane	4.43	.945	23
Male	As-Built	2.96	1.400	27
	Bike Lane	3.85	.770	27
	Protected Bike Lane	3.85	1.167	27

Mauchly's Test of Sphericity[a]

Measure: Perceived_Safety

Gender		df	Sig.	Epsilon[b]

	Within Subjects Effect	Mauchly's W	Approx. Chi-Square			Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Female	Environments	.720	6.903	2	.032	.781	.830	.500
Male	Environments	.372	24.689	2	.000	.614	.629	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Perceived_Safety

Gender	Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Female	Environments	Sphericity Assumed	65.304	2	32.652	43.063	.000	.662
		Greenhouse-Geisser	65.304	1.562	41.800	43.063	.000	.662
		Huynh-Feldt	65.304	1.660	39.332	43.063	.000	.662
		Lower-bound	65.304	1.000	65.304	43.063	.000	.662
	Error(Environments)	Sphericity Assumed	33.362	44	.758			
		Greenhouse-Geisser	33.362	34.371	.971			
		Huynh-Feldt	33.362	36.527	.913			
		Lower-bound	33.362	22.000	1.516			
Male	Environments	Sphericity Assumed	14.222	2	7.111	5.679	.006	.179
		Greenhouse-Geisser	14.222	1.229	11.573	5.679	.018	.179
		Huynh-Feldt	14.222	1.259	11.299	5.679	.017	.179
		Lower-bound	14.222	1.000	14.222	5.679	.025	.179
	Error(Environments)	Sphericity Assumed	65.111	52	1.252			
		Greenhouse-Geisser	65.111	31.950	2.038			
		Huynh-Feldt	65.111	32.726	1.990			
		Lower-bound	65.111	26.000	2.504			

Pairwise Comparisons

Measure: Perceived_Safety

Gender	(I) Environments	(J) Environments	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Female	1	2	-1.783*	.177	.000	-2.242	-1.323
		3	-2.261*	.296	.000	-3.029	-1.493
	2	1	1.783*	.177	.000	1.323	2.242
		3	-.478	.280	.306	-1.204	.248
	3	1	2.261*	.296	.000	1.493	3.029
		2	.478	.280	.306	-.248	1.204
Male	1	2	-.889*	.241	.003	-1.505	-.273

	3	-.889	.408	.115	-1.932	.154
2	1	.889*	.241	.003	.273	1.505
	3	.000	.233	1.000	-.595	.595
3	1	.889	.408	.115	-.154	1.932
	2	.000	.233	1.000	-.595	.595

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

For women, protected bike lane safety means are significantly different from those of the as-built environment. Similarly bike lane perceived safety means are significantly different from those of the as-built environment. The bike lane and the protected bike lane are not significantly different from each other.

For men, only the perceived safety means for the as-built environment and bike lane environment are statistically different.

Bicycling Attitude Effects

Repeated Measures ANOVA of perceived safety question responses with bicycling attitude as between-subject effect.

Descriptive Statistics

	Attitude	Mean	Std. Deviation	N
As-Built	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	2.77	1.142	26
	"Interested but Concerned" - I like the idea of riding but have concerns	1.92	1.115	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	3.22	1.093	9
	Total	2.63	1.196	48
Bike Lane	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	4.00	.800	26
	"Interested but Concerned" - I like the idea of riding but have concerns	3.77	.725	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	3.89	.782	9
	Total	3.92	.767	48
Protected Bike Lane	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	4.00	1.233	26
	"Interested but Concerned" - I like the idea of riding but have concerns	4.23	.599	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	4.22	1.394	9
	Total	4.10	1.115	48

Mauchly's Test of Sphericity[a]

Measure: Perceived_Safety

Mauchly's W		df	Sig.	Epsilon[b]

Within Subjects Effect		Approx. Chi-Square			Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.532	27.777	2	.000	.681	.726	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.
a. Design: Intercept + Attitude
Within Subjects Design: Environments
b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Sphericity not met, use Greenhouse-Geisser adjustment.

Tests of Within-Subjects Effects

Measure: Perceived_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	51.868	2	25.934	23.583	.000	.344
	Greenhouse-Geisser	51.868	1.362	38.074	23.583	.000	.344
	Huynh-Feldt	51.868	1.453	35.706	23.583	.000	.344
	Lower-bound	51.868	1.000	51.868	23.583	.000	.344
Environments * Attitude	Sphericity Assumed	7.428	4	1.857	1.689	.160	.070
	Greenhouse-Geisser	7.428	2.725	2.726	1.689	.183	.070
	Huynh-Feldt	7.428	2.905	2.557	1.689	.179	.070
	Lower-bound	7.428	2.000	3.714	1.689	.196	.070
Error(Environments)	Sphericity Assumed	98.974	90	1.100			
	Greenhouse-Geisser	98.974	61.304	1.614			
	Huynh-Feldt	98.974	65.370	1.514			
	Lower-bound	98.974	45.000	2.199			

Interaction effect is not significant.

6.4.2 Stated Preference Survey: "How safe did you feel concerning the cars driving past you while you were biking in the bike lane/biking in the protected bike lane with pylons/biking in the road with no bike infrastructure?"

Within-Subjects Effects

Repeated Measures ANOVA of traffic safety question responses.

Descriptive Statistics

	Mean	Std. Deviation	N
Traffic Safety As Built	2.50	1.147	50
Traffic Safety Bike Lane	3.54	1.034	50
Traffic Safety Prot Bike Lane	4.34	.895	50

Sphericity. The p value is greater than 0.05, so we have met the assumption of sphericity.

Mauchly's Test of Sphericity[a]

Measure: Traffic_Safety

					Epsilon[b]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.888	5.684	2	.058	.900	.932	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Within-subjects tests. P < 0.05, therefore the means of traffic safety between the different environments are not equal. We look at pairwise tests to determine which means are different.

Tests of Within-Subjects Effects

Measure: Traffic_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	85.120	2	42.560	44.586	<.001	.476
	Greenhouse-Geisser	85.120	1.799	47.313	44.586	<.001	.476
	Huynh-Feldt	85.120	1.863	45.680	44.586	<.001	.476
	Lower-bound	85.120	1.000	85.120	44.586	<.001	.476
Error(Environments)	Sphericity Assumed	93.547	98	.955			
	Greenhouse-Geisser	93.547	88.155	1.061			
	Huynh-Feldt	93.547	91.306	1.025			
	Lower-bound	93.547	49.000	1.909			

Pairwise Comparisons with Bonferonni correction.

Pairwise Comparisons

Measure: Traffic_Safety

(I) Environments	(J) Environments	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-1.040*	.176	<.001	-1.476	-.604
	3	-1.840*	.226	<.001	-2.399	-1.281
2	1	1.040*	.176	<.001	.604	1.476
	3	-.800*	.181	<.001	-1.248	-.352
3	1	1.840*	.226	<.001	1.281	2.399
	2	.800*	.181	<.001	.352	1.248

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

The traffic safety responses are significantly different between all three environments.

Gender Effects

Repeated Measures ANOVA of traffic safety question responses with gender as between-subject effect.

Descriptive Statistics

	Gender	Mean	Std. Deviation	N
Traffic Safety As Built	Female	2.30	1.105	23
	Male	2.67	1.177	27
	Total	2.50	1.147	50
Traffic Safety Bike Lane	Female	3.52	1.039	23
	Male	3.56	1.050	27
	Total	3.54	1.034	50
Traffic Safety Prot Bike Lane	Female	4.39	.941	23
	Male	4.30	.869	27
	Total	4.34	.895	50

Mauchly's Test of Sphericity[a]

Measure: Traffic_Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.893	5.304	2	.071	.904	.956	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Gender
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Sphericity assumption is met, $p > 0.05$.

Tests of Within-Subjects Effects

Measure: Traffic_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	86.288	2	43.144	44.939	<.001	.484
	Greenhouse-Geisser	86.288	1.807	47.748	44.939	<.001	.484
	Huynh-Feldt	86.288	1.913	45.111	44.939	<.001	.484
	Lower-bound	86.288	1.000	86.288	44.939	<.001	.484
Environments * Gender	Sphericity Assumed	1.381	2	.691	.719	.490	.015
	Greenhouse-Geisser	1.381	1.807	.764	.719	.477	.015
	Huynh-Feldt	1.381	1.913	.722	.719	.484	.015
	Lower-bound	1.381	1.000	1.381	.719	.401	.015
Error(Environments)	Sphericity Assumed	92.165	96	.960			
	Greenhouse-Geisser	92.165	86.743	1.063			
	Huynh-Feldt	92.165	91.814	1.004			
	Lower-bound	92.165	48.000	1.920			

There is no significant interaction between gender and the different environments. $F(2,96) = 0.719$, $p=0.490$

T-tests:
As-Built:

Group Statistics

	Gender	N	Mean	Std. Deviation	Std. Error Mean
AsBuiltSpeed	Male	26	14.77856183	3.850883092	.7552203089
	Female	23	15.44983838	4.095127519	.8538931152

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
						Significance				95%
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	
AsBuiltSpeed	Equal variances assumed	.044	.836	-.591	47	.279	.557	-.671276553	1.135582544	-2.
	Equal variances not assumed			-.589	45.422	.279	.559	-.671276553	1.139952265	-2.

Bike Lane

Group Statistics

	Gender	N	Mean	Std. Deviation	Std. Error Mean
BikeLaneSpeed	Male	26	14.66785343	3.576338086	.7013776034
	Female	23	15.17027588	4.037760920	.8419313523

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interv Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	U
BikeLaneSpeed	Equal variances assumed	.694	.409	-.462	47	.323	.646	-.502422454	1.087556247	-2.69030342	1.68
	Equal variances not assumed			-.458	44.339	.324	.649	-.502422454	1.095800595	-2.71038657	1.70

Protected Bike Lane

Group Statistics

	Gender	N	Mean	Std. Deviation	Std. Error Mean
ProtectedLaneSpeed	Male	26	13.70383942	4.289535983	.8412472186
	Female	23	14.05464090	4.088018620	.8524108072

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means							
						Significance				95% Confidence Interv Difference	
		F	Sig.	t	df	One-Sided p	Two-Sided p	Mean Difference	Std. Error Difference	Lower	U
ProtectedLaneSpeed	Equal variances assumed	.023	.880	-.292	47	.386	.772	-.350801484	1.201228792	-2.76736211	2.06
	Equal variances not assumed			-.293	46.722	.385	.771	-.350801484	1.197623091	-2.76048717	2.05

Bicycling Attitude Effects

Repeated Measures ANOVA of perceived safety question responses with bicycling attitude as between-subject effect.

Descriptive Statistics

	Attitude	Mean	Std. Deviation	N
Traffic Safety As Built	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	2.38	1.169	26
	"Interested but Concerned" - I like the idea of riding but have concerns	2.31	1.182	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	3.22	.972	9
	Total	2.52	1.167	48
Traffic Safety Bike Lane	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	3.58	1.172	26
	"Interested but Concerned" - I like the idea of riding but have concerns	3.46	.877	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	3.67	.866	9
	Total	3.56	1.029	48
Traffic Safety Prot Bike Lane	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	4.35	1.018	26
	"Interested but Concerned" - I like the idea of riding but have concerns	4.38	.506	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	4.22	1.093	9
	Total	4.33	.907	48

Mauchly's Test of Sphericity[a]

Measure: Traffic_Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.896	4.847	2	.089	.906	.983	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Attitude
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Sphericity is met:

Tests of Within-Subjects Effects

Measure: Traffic_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	56.258	2	28.129	28.812	<.001	.390
	Greenhouse-Geisser	56.258	1.811	31.063	28.812	<.001	.390
	Huynh-Feldt	56.258	1.967	28.608	28.812	<.001	.390
	Lower-bound	56.258	1.000	56.258	28.812	<.001	.390
Environments * Attitude	Sphericity Assumed	4.037	4	1.009	1.034	.394	.044
	Greenhouse-Geisser	4.037	3.622	1.114	1.034	.391	.044
	Huynh-Feldt	4.037	3.933	1.026	1.034	.394	.044
	Lower-bound	4.037	2.000	2.018	1.034	.364	.044
Error(Environments)	Sphericity Assumed	87.866	90	.976			
	Greenhouse-Geisser	87.866	81.498	1.078			
	Huynh-Feldt	87.866	88.493	.993			
	Lower-bound	87.866	45.000	1.953			

No significant interaction between attitude and environments.

High and Low Vehicle Volume Effects

Repeated Measures ANOVA of traffic safety question responses with traffic volume as between-subject effect.

Descriptive Statistics

	HighLow	Mean	Std. Deviation	N
Traffic Safety As Built	High	2.46	1.104	26
	Low	2.54	1.215	24
	Total	2.50	1.147	50
Traffic Safety Bike Lane	High	3.58	1.137	26
	Low	3.50	.933	24
	Total	3.54	1.034	50
Traffic Safety Prot Bike Lane	High	4.46	.859	26
	Low	4.21	.932	24
	Total	4.34	.895	50

Mauchly's Test of Sphericity[a]

Measure: Traffic_Safety

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt	Epsilon[b] Lower-bound
Environments	.892	5.392	2	.067	.902	.955	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + HighLow
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Traffic_Safety

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Environments	Sphericity Assumed	84.374	2	42.187	43.617	<.001	.476
	Greenhouse-Geisser	84.374	1.804	46.759	43.617	<.001	.476
	Huynh-Feldt	84.374	1.910	44.181	43.617	<.001	.476
	Lower-bound	84.374	1.000	84.374	43.617	<.001	.476
Environments * HighLow	Sphericity Assumed	.694	2	.347	.359	.699	.007
	Greenhouse-Geisser	.694	1.804	.385	.359	.678	.007
	Huynh-Feldt	.694	1.910	.363	.359	.690	.007
	Lower-bound	.694	1.000	.694	.359	.552	.007
Error(Environments)	Sphericity Assumed	92.853	96	.967			
	Greenhouse-Geisser	92.853	86.613	1.072			
	Huynh-Feldt	92.853	91.668	1.013			
	Lower-bound	92.853	48.000	1.934			

No interaction between traffic volume and environments.

6.5 SIMULATOR OUTPUT RESULTS

6.5.1 Speed Results

Repeated Measures ANOVA of speeds in each bicycling environment.

Within-Subjects Factors

Measure: Speed

Environments	Dependent Variable
1	AsBuiltSpeed
2	BikeLaneSpeed
3	ProtectedLaneSpeed

Descriptive Statistics

	Mean	Std. Deviation	N
AsBuiltSpeed	15.09365082	3.940107205	49
BikeLaneSpeed	14.90368438	3.768047682	49
ProtectedLaneSpeed	13.86850134	4.156236644	49

Mauchly's Test of Sphericity[a]

Measure: Speed

					Epsilon[b]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environments	.931	3.375	2	.185	.935	.972	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environments

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Speed

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Environments	Sphericity Assumed	42.608	2	21.304	5.822	.004
	Greenhouse-Geisser	42.608	1.870	22.781	5.822	.005
	Huynh-Feldt	42.608	1.943	21.925	5.822	.004
	Lower-bound	42.608	1.000	42.608	5.822	.020
Error(Environments)	Sphericity Assumed	351.312	96	3.660		
	Greenhouse-Geisser	351.312	89.779	3.913		
	Huynh-Feldt	351.312	93.284	3.766		
	Lower-bound	351.312	48.000	7.319		

Pairwise Comparisons

Measure: Speed

(I) Environments	(J) Environments	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	.190	.333	1.000	-.637	1.017
	3	1.225*	.401	.011	.230	2.220
2	1	-.190	.333	1.000	-1.017	.637
	3	1.035	.420	.052	-.006	2.076
3	1	-1.225*	.401	.011	-2.220	-.230
	2	-1.035	.420	.052	-2.076	.006

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Gender Effects

Repeated Measures ANOVA of speeds in each environment with gender as between-subject effect.

Descriptive Statistics

	Gender	Mean	Std. Deviation	N
AsBuiltSpeed	Female	15.44983838	4.095127519	23
	Male	14.77856183	3.850883092	26
	Total	15.09365082	3.940107205	49
BikeLaneSpeed	Female	15.17027588	4.037760920	23
	Male	14.66785343	3.576338086	26
	Total	14.90368438	3.768047682	49
ProtectedLaneSpeed	Female	14.05464090	4.088018620	23
	Male	13.70383942	4.289535983	26
	Total	13.86850134	4.156236644	49

Mauchly's Test of Sphericity[a]

Measure: Speed

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environment	.931	3.305	2	.192	.935	.993	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + Gender
Within Subjects Design: Environment

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Speed

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Environment	Sphericity Assumed	43.031	2	21.515	5.767	.004
	Greenhouse-Geisser	43.031	1.870	23.007	5.767	.005
	Huynh-Feldt	43.031	1.986	21.662	5.767	.004
	Lower-bound	43.031	1.000	43.031	5.767	.020
Environment * Gender	Sphericity Assumed	.627	2	.314	.084	.919
	Greenhouse-Geisser	.627	1.870	.335	.084	.908
	Huynh-Feldt	.627	1.986	.316	.084	.918
	Lower-bound	.627	1.000	.627	.084	.773
Error(Environment)	Sphericity Assumed	350.685	94	3.731		
	Greenhouse-Geisser	350.685	87.906	3.989		
	Huynh-Feldt	350.685	93.362	3.756		
	Lower-bound	350.685	47.000	7.461		

Bicycling Attitude Effects

Repeated Measures ANOVA of speeds in each environment with bicycling attitude as between-subject effect.

Descriptive Statistics

	Attitude	Mean	Std. Deviation	N
AsBuiltSpeed	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	15.70437223	3.922501776	25
	"Interested but Concerned" - I like the idea of riding but have concerns	13.50021211	3.143971702	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	15.19660224	4.966970377	9
	Total	14.99747837	3.976119876	47
BikeLaneSpeed	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	15.47575945	3.799095185	25
	"Interested but Concerned" - I like the idea of riding but have concerns	13.91153975	3.080343562	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	14.70076290	4.924408083	9
	Total	14.89469934	3.832358362	47
ProtectedLaneSpeed	"Enthused and Confident" -I like to ride and will do so with dedicated infrastructure	14.06182500	3.743240899	25
	"Interested but Concerned" - I like the idea of riding but have concerns	13.35577245	3.385590124	13
	"Strong and Fearless" - I will ride anywhere, no matter the facilities provided	13.72339688	6.317518076	9
	Total	13.80172849	4.163639861	47

Mauchly's Test of Sphericity[a]

Measure: Speed

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bo
Environment	.929	3.173	2	.205	.934	1.000	

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportio to an identity matrix.

a. Design: Intercept + Attitude
Within Subjects Design: Environment

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Speed

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Environment	Sphericity Assumed	28.376	2	14.188	3.765	.027
	Greenhouse-Geisser	28.376	1.867	15.197	3.765	.030
	Huynh-Feldt	28.376	2.000	14.188	3.765	.027
	Lower-bound	28.376	1.000	28.376	3.765	.059
Environment * Attitude	Sphericity Assumed	10.574	4	2.643	.701	.593
	Greenhouse-Geisser	10.574	3.734	2.831	.701	.584
	Huynh-Feldt	10.574	4.000	2.643	.701	.593
	Lower-bound	10.574	2.000	5.287	.701	.501
Error(Environment)	Sphericity Assumed	331.659	88	3.769		
	Greenhouse-Geisser	331.659	82.156	4.037		
	Huynh-Feldt	331.659	88.000	3.769		
	Lower-bound	331.659	44.000	7.538		

Traffic Volume Effects:

Repeated Measures ANOVA of speeds in each environment with traffic volume as between-subject effect.

Descriptive Statistics

	HighLow	Mean	Std. Deviation	N
AsBuiltSpeed	High	14.77985583	4.011728198	26
	Low	15.44837560	3.915993077	23
	Total	15.09365082	3.940107205	49
BikeLaneSpeed	High	14.96696984	3.780196447	26
	Low	14.83214429	3.837872431	23
	Total	14.90368438	3.768047682	49
ProtectedLaneSpeed	High	13.40758181	3.734072300	26
	Low	14.38954081	4.616258034	23
	Total	13.86850134	4.156236644	49

Mauchly's Test of Sphericity[a]

Measure: Speed

					Epsilon[b]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environment	.930	3.338	2	.188	.935	.993	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept + HighLow
Within Subjects Design: Environment

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: Speed

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Environment	Sphericity Assumed	41.097	2	20.548	5.628	.005
	Greenhouse-Geisser	41.097	1.869	21.987	5.628	.006
	Huynh-Feldt	41.097	1.985	20.702	5.628	.005
	Lower-bound	41.097	1.000	41.097	5.628	.022
Environment * HighLow	Sphericity Assumed	8.099	2	4.049	1.109	.334
	Greenhouse-Geisser	8.099	1.869	4.333	1.109	.331
	Huynh-Feldt	8.099	1.985	4.080	1.109	.334
	Lower-bound	8.099	1.000	8.099	1.109	.298
Error(Environment)	Sphericity Assumed	343.214	94	3.651		
	Greenhouse-Geisser	343.214	87.852	3.907		
	Huynh-Feldt	343.214	93.300	3.679		
	Lower-bound	343.214	47.000	7.302		

6.5.2 Braking Results

Repeated Measures ANOVA of braking squeeze values in each environment.

Within-Subjects Factors

Measure: Squeeze_Braking_Val

Environment	Dependent Variable
1	AverageSqueezeBrakingValueAsBuilt
2	AverageSqueezeBrakingValueBikeLane
3	AverageSqueezeBrakingValueProtectedLane

Descriptive Statistics

	Mean	Std. Deviation	N
Average Squeeze Braking Value	.0128781011	.0382425751	49
Average Squeeze Braking Value	.0076441746	.0205373755	49
Average Squeeze Braking Value	.0215869436	.0458561359	49

Mauchly's Test of Sphericity[a]

Measure: Squeeze_Braking_Value

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Environment	.739	14.203	2	<.001	.793	.816	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: Environment

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Sphericity not met. Use Huynh-Feldt correction.

Tests of Within-Subjects Effects

Measure: Squeeze_Braking_Value

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Environment	Sphericity Assumed	.005	2	.002	2.613	.079
	Greenhouse-Geisser	.005	1.586	.003	2.613	.092
	Huynh-Feldt	.005	1.632	.003	2.613	.090
	Lower-bound	.005	1.000	.005	2.613	.113
Error(Environment)	Sphericity Assumed	.089	96	.001		
	Greenhouse-Geisser	.089	76.142	.001		
	Huynh-Feldt	.089	78.316	.001		
	Lower-bound	.089	48.000	.002		

Mean squeeze values are significantly different in each environment at $p<0.1$

Pairwise Comparisons

Measure: Squeeze_Braking_Value

(I) Environment	(J) Environment	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	.005	.005	.916	-.007	.018
	3	-.009	.008	.764	-.027	.010
2	1	-.005	.005	.916	-.018	.007
	3	-.014*	.006	.049	-.028	-6.144E-5
3	1	.009	.008	.764	-.010	.027
	2	.014*	.006	.049	6.144E-5	.028

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Average braking squeeze value is significantly higher in protected bike lane compared to the bike lane environment. P=0.049.