# Characterizing Bicyclists Behavior in Overtaking Scenarios Over Different Road Infrastructures

Eugene Raymond Crump IV

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Biomedical Engineering

Luke E. Riexinger, Chair
Miguel A. Perez, Co-Chair
Feng Guo

April 26, 2024
Blacksburg, Virginia

Keywords: Overtaking
Virtual Reality
Bicyclist
Behavior
Infrastructure
ADAS
AEB

Characterizing Bicyclists Behavior in Overtaking Scenarios Over Different Road Infrastructures

Eugene Raymond Crump IV

ABSTRACT

Fatal vehicle-bicycle crashes have increased in the United States while cyclist crashes often go unreported. The underreporting of all cyclist crashes results in the overall pre-crash behavior of the cyclists being unknown. What is known is that the most fatal bicycle crash scenario occurs when a vehicle performs an overtaking maneuver. It is crucial to find effective strategies to mitigate these crashes. Vision Zero aims to eliminate all traffic fatalities and disabling injuries by the year 2050 through the implementation of the safe system approach. One of their approaches is using active safety systems like bicycle detecting automatic emergency braking.

The purpose of this study was to characterize bicyclist behavior to enhance the crash avoidance potential of advanced driver assistance systems and improve safety for cyclists. An analysis on fatal crashes involving bicyclists was conducted to determine scenarios for testing bicyclist-vehicle interactions on roadways using virtual reality (VR). VR testing was conducted to capture and analyze bicyclist dynamics. Most fatal bicycle crashes occurred when motorists overtook cyclists, especially when cyclists are travelling in a travel lane in the same direction as traffic. These crashes often happen in densely populated areas with favorable weather conditions. This information was used to construct scenarios representing common fatal bicycle crash scenarios. From the analysis, four scenarios were developed. The first scenario was an overtaking scenario with the cyclist traveling in the same direction as traffic, in a travel lane without a bicycle lane or shoulder.

The second, third and fourth scenarios were variations of the first to include a bike lane, shoulder, and both a bike lane and a shoulder to analyze the behavior difference due to the inclusion of each.

Participants were immersed in a VR simulator that used the combination of a VR headset and a custom-built stationary bicycle. Eighteen individuals were recruited with an average age of 22.7 years. Participants experienced all four scenarios, and their speed, glance, lane position, and standard deviation of lane position were collected and analyzed. The speed for each road type and overtaking phase did not vary significantly, with an average of 4.9 m/s. In the case where there was neither a bike lane or a shoulder, the cyclists looked towards the vehicle more than the other scenarios. As for the lane position, the scenario where the cyclist had neither a shoulder or a bike lane, led to a closer vehicle-bicycle relative position than the other three scenarios. As for standard deviation of lane position, the road with neither a shoulder or bike lane had the largest interquartile range (IQR) and average and the road with both a shoulder and bike lane had the smallest IQR. This implies a lower predictability of the cyclist’s movements when they are riding on a roadway with no support lane. Following the testing, participants rated the perceived realism and interactiveness of the VR world and their comfort in each road design. Most of the participants mentioned that having some allocated space felt more comfortable and lowered their sense of danger.

To enhance cyclist safety, adopting Euro NCAP testing for AEB systems in the US is recommended. This form of testing could lead to improvements in AEB systems, reducing crashes with cyclists and injury severity. In terms of road infrastructure improvements increasing the number of bike lanes, adding wider shoulders, or widening lanes could also enhance cyclist safety on roadways.

Characterizing Bicyclists Behavior in Overtaking Scenarios Over Different Road Infrastructures

Eugene Raymond Crump IV

GENERAL AUDIENCE ABSTRACT

Fatal crashes between vehicles and bicycles have increased in the United States while cyclist crashes often go unreported. The underreporting of all cyclist crashes results in the overall pre-crash behavior of the cyclists being unknown. What is known is that the most fatal bicycle crash scenario occurs when a vehicle performs an overtaking maneuver. It is crucial to find effective strategies to reduce the severity and occurrences of these crashes. A traffic safety initiative called Vision Zero aims to eliminate all traffic fatalities and disabling injuries by the year 2050 through the implementation of the safe system approach. One of their approaches is having technology installed in vehicles to assist drivers in mitigating accidents, such as bicycle detecting automatic emergency braking.

The purpose of this study was to characterize bicyclist behavior to enhance the crash avoidance potential of advanced driver assistance systems and improve safety for cyclists. An analysis on fatal crashes involving bicyclists was conducted to determine scenarios for testing bicyclist-vehicle interactions on roadways using virtual reality (VR). VR testing was conducted to capture and analyze bicyclist dynamics. Most fatal bicycle crashes occurred when motorists overtook cyclists, especially when cyclists are travelling in a travel lane in the same direction as traffic. Overtaking is when a vehicle is travelling faster than the cyclist and passes them. Crashes between vehicles and bicycles often happen in densely populated areas with favorable weather conditions. This information was used to construct scenarios representing common fatal bicycle crash scenarios. From the

analysis, four scenarios were developed. The first scenario was an overtaking scenario with the cyclist traveling in the same direction as traffic, in a travel lane without a bicycle lane or shoulder. The second, third and fourth scenarios were variations of the first to include a bike lane, shoulder, and both a bike lane and a shoulder to analyze the behavior difference due to the inclusion of each. Where the shoulder is additional paved area alongside the travel lane.

Participants were immersed in a VR simulator that used the combination of a VR headset and a custom-built stationary bicycle. Eighteen individuals were recruited with an average age of 22.7 years. Participants experienced all four scenarios, and their speed, glance, lane position, and standard deviation of lane position were collected and analyzed. The speed for each road type and overtaking phase did not vary significantly, with an average of 4.9 m/s. In the case where there was neither a bike lane or a shoulder, the cyclists looked towards the vehicle more than the other scenarios. As for the lane position, the scenario where the cyclist had neither a shoulder or a bike lane, led to a closer relative position between the vehicles and bicyclists than the other three scenarios. As for standard deviation of lane position or lateral movement, the road with neither a shoulder or bike lane had the largest interquartile range (IQR) and average and the road with both a shoulder and bike lane had the smallest IQR. Where IQR is the statistical measure indicating the dispersion of data between the first quartile and the third quartile. This implies a lower predictability of the cyclist’s movements when they are riding on a roadway with no support lane. Following the testing, participants rated the perceived realism and interactiveness of the VR world and their comfort in each road design. Most of the participants mentioned that having some allocated space felt more comfortable and lowered their sense of danger.

To enhance cyclist safety, adopting the European New Car Assessment Program (Euro NCAP) testing for automatic emergency braking systems in the US is recommended. This form of testing could lead to improvements in automatic emergency braking systems, reducing crashes with cyclists and injury severity. For road infrastructure improvements increasing the number of bike lanes, adding wider shoulders, or widening lanes could also enhance cyclist safety on roadways.

# Acknowledgements

I extend my gratitude to my committee, comprised of my Advisor, Dr. Luke E. Riexinger, Co-Chair Dr. Miguel Perez, and Dr. Feng Guo, whose guidance and expertise have been instrumental throughout the process of completing this thesis.

I am also appreciative of the efforts of the senior design team, including Nikhil Pradeep, Macs Tantawi, Neffisah D'odoo, and Sam Schilbe, who developed the stationary bicycle utilized in participant testing.

Special thanks to Abigail Kleinschmidt for her contributions to the stationary bike, Edward Shangin for his assistance in participant data collection, and Jonathan Bradley and Alex Giovanneli for their support in the development of the VR environment.

I am grateful to GEM and New Horizon’s for their financial support, which enabled me to complete my studies. Additionally, I extend my appreciation to Dr. Tremayne Waller and Amanda Covey for their support and advocacy throughout this journey.

# Table of Contents

# List of Figures

## List of Tables

# Chapter 1: Introduction and Background

Fatal vehicle-bicycle crashes have increased from 621 in 2010 to 961 in 2021 in the United States [1]. It is crucial to find effective strategies to mitigate these crashes. The Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA), and Federal Motor Carrier Safety Administration (FMCSA) are working with the National Safety Council (NSC) to align with the goals and principles of Vision Zero to accomplish the feat of zero traffic deaths by 2050 [2]. Vision Zero aims to eliminate all traffic fatalities and disabling injuries through the implementation of the safe system approach. The safe system approach is a multidisciplinary approach designed to bring individuals together to address the complex problem of designing road systems and policies to ensure the inevitable mistakes caused by human error do not result in severe injuries or fatalities. Vision Zero strategies include bike lanes, intersection delineators, active safety systems, and no right on red. Automotive companies are also equipping vehicles with active safety systems to potentially avoid or mitigate crashes, like automatic emergency braking.

## Bicycle Crashes

According to NHTSA, 938 cyclists were involved in a fatal crash in 2020, which accounts for 2.4% of all fatal crashes [3]. The number of fatally injured cyclists increased by 9% from 2019 while the overall fatalities increased by 7.3% [4]. NHTSA estimated about 39,000 cyclists were injured, and males had a 7 times higher fatality rate and a 4 times higher injury rate than females. In addition, 79% of fatal cyclist crashes occurred in urban area and 34% of all fatal cyclist crashes involved the use of alcohol (0.01g/dL BAC) [3]. In 22% of these fatal bicycle crashes the cyclist had a BAC of 0.01 g/dL, and about 17% of cyclists had a BAC of 0.08 g/dL or higher. The percentage of overall and bicycle fatal crashes involving alcohol, however, had decreased from 2011 to 2020 [3].

Fredriksson et al. (2014) studied different vehicle-bicyclist crash scenarios using the Swedish Transport Administration fatal database and the Swedish Traffic Accident Data Acquisition (STRADA) database [5]. Most non-fatal bicyclist crashes happened in daylight and dry conditions, and during the summer season. This correlates to when bicycles tend to be used. During most vehicle-bicycle crashes, bicyclists contacted the front or side of the vehicle. Most of the fatal crashes and AIS2+ injury crashes occurred in urban intersections where the cyclist crossed the path of a car driving straight. Injuries most commonly occurred in 50 km/h areas while fatalities occurred in 50 km/h to 90 km/h areas. AIS2+ injury crashes occurred most for male cyclists in the age range of 20-years-old to 60-years-old while crashes for 60-years-old to 90-years-old tended to result in fatalities. The most common bicycle crash scenarios were when the vehicle was traveling straight and the bicyclist crossed the roadway from either the right or left in an urban area, bike turning in front of an approaching vehicle in the same lane in a rural area, and a vehicle turning left and a bike crossing the road from the right in an urban junction [5].

Macioszek and Grana (2021) investigated police reported crashes in Poland in 2019 between bicyclists and vehicles from the Accident and Collision Recording System (ACRS) and the Traffic Control Center (TCC) [6]. The goal of their study was to identify factors that influence the occurrence and severity of bicyclist injury in vehicle-bicyclist crashes. The occurrence and probability of the severity of cyclist injuries can be influenced by a multitude of factors. These include an increase due to the driver being male, the driver or the cyclist being under 60 years-old, the driver or the cyclist being under the influence of alcohol, the driver exceeding the speed limit, and the cyclist traveling faster than 30 km/h. Other factors such as the vehicle being a truck, a crash occurring on a roadway, a crash occurring at night, and the crash being head-on also contributed to increasing injury severity and probability of crash occurrence for cyclists [6]. In contrast, Olesen et al. (2021) ran a one-year longitudinal study on 6,793 cyclists in Denmark where 349 single bicycle crashes were reported. Of the 349 reported crashes, 17.8% of the cyclists reported getting medical treatment. These crashes were generally a result of poor road maintenance and poor cyclist infrastructure. Resulting recommendations emphasized improving infrastructure for the cyclists' safety to reduce the estimated attributable hospital cost of about $1,850 USD [7].

### Underreporting

Cyclist crashes often go unreported. The main cases that go underreported include low injury severity crashes and single bicycle crashes [8]. Shinar et al. conducted a study looking at survey data in the COST TU1101 action "Towards safer bicycling through optimization of bicycle helmets and usage." The results showed that, across 17 countries, an average of 90% of all bicycle crashes were unreported to the police [9]. Although the main cases that go underreported tend to be low severity and single bicycle crashes [8], crashes between cyclists and motorists sometimes also go underreported. This results in the pre-crash behavior of the cyclists for these unreported situations being generally unknown.

### Overtaking Bicycle Crashes

The most common fatal bicycle crash scenario occurs when a vehicle performs a maneuver called overtaking, which is when a vehicle is traveling faster than a cyclist and passes them [10]. Rasch et al. (2020) performed an experiment on a test track to understand how oncoming traffic and the position of the cyclist within the lane influence overtaking. Their study investigated the time gap between the current vehicle and the oncoming vehicle, along with the cyclist's lateral position for four different overtaking phases: approaching, steering away, passing, and returning. Driver strategies for overtaking were related to gender, the time gap, and cyclist lateral position [10]. If the driver was a female and the time gap was shorter there was a higher likelihood of an “accelerative” overtaking maneuver being performed compared to a “flying” overtaking maneuver. “Flying” overtaking happens when the vehicle travels at a constant speed when overtaking, while “accelerative” overtaking happens when the vehicle changes speed during overtaking.

Similarly, Llorca et al. (2017) conducted a study with a bicycle equipped with laser rangefinders, GPS trackers, and three video cameras: front view, rear view, and left view. The participants cycled on seven rural road segments between 15 and 25 km/h and completed 2,928 overtaking events. Cyclists perceived that traveling at higher speeds within the presence of heavy vehicles was the highest risk scenario. According to the participants, the combination of larger lateral separation and lower speed were related to a lower perception of risk [11]. Walker et al. (2007) also ran a naturalistic study with an instrumented bicycle to gather data on overtaking motorists [12]. The goal of their study was to investigate the behavior of motorists when overtaking a bicyclist and what factors influenced that behavior. When the cyclist was perceived as male, wore a helmet, or rode away from the edge of the road, the overtaking vehicle passed closer [12]. Likewise, Vu et al. (2021) investigated driving styles while overtaking a vulnerable road user who moves along the shoulder in urban roads [13]. They analyzed four different driving styles while approaching and passing vulnerable road users. Results indicated that drivers performed avoidance maneuvers even if there was no clear risk of collision with vulnerable road users. Drivers in Vu et al. tended to have unique perceptions about the lateral passing gap and overtaking strategy. Road characteristics, vehicle’s initial speed on overtaking strategy, and vulnerable road user minimum lateral passing gap were statistically significant [13]. If the road lane was wider, the lateral passing gap was larger, and the drivers slowed down less. If the initial speed was higher, the lateral passing gap was smaller, and the drivers slowed down more.

Lee et al. (2020) modeled braking and steering maneuvers from field data of cyclists’ obstacle avoidance within their modeled comfort zone [14]. They found that when cyclists avoided obstacles by braking, they kept a constant deceleration and maintained an almost constant time to collision. When cyclists avoided obstacles by steering, they maintained a constant distance from the object, independent of speed. The higher the speed, the more the steering maneuvers were temporally delayed compared to braking maneuvers [14]. In turn, Farah et al. (2019) designed a driving simulator study to assess driver decision-making during the overtaking. Binary logistic-regression models with mixed effects predicted if the type of overtaking strategy would be flying or accelerative. Driving speeds were found to significantly affect the strategy. The results showed that the lateral comfort distance was mostly affected by the longitudinal distance between the subject vehicle and the oncoming vehicle [15]. Rasch et al. (2022) instead measured the perceived safety of drivers in a test-track experiment in Sweden. They developed Bayesian ordinal logistic regression models of perceived safety scores. Their results showed that drivers’ perceived safety decreased when there was an oncoming vehicle with a low time-to-collision. They also investigated the perceived safety of cyclists in a field test in Spain. The cyclists’ perceived safety decreased when there was a small lateral clearance and a high overtaking speed [16].

Liu et al. (2017) observed bicyclist behavior during overtaking based on vehicle mounted cameras from the Transportation Active Safety Institute (TASI) 110-car naturalistic driving data

[17]. They found the median lateral position of the bicyclists moving in the direction parallel to the vehicle path was 3.8 m and the median lateral position of the bicyclists traveling on the left side was 4.4 m. The median cyclist speed was 7.5 m/s or about 17 mph [17]. Likewise, Cobb et al. (2021) investigated how cyclists interacted with their environment to get a better understanding of their abilities and limitations. Their performance was based on velocity, horizontal displacement, and physiological responses. When bicyclists were on roads without a bike lane, their galvanic skin response was higher, and they drove slower. Cobb et al. also found that the riders were less comfortable when there was more traffic, but their velocity did not change [18].

### Intersection Bicycle Crashes

Thomas et al. (2019) conducted a study to compare fatal bicyclist crash types from the Fatal Analysis Reporting System (FARS) with all-severity bicyclist collisions from North Carolina and Boulder, Colorado. It was found that between 2014 to 2016, 30% of fatal bicyclist urban crashes and 6% of fatal bicyclist rural crashes occurred in an intersection. In North Carolina, 42% of bicyclist urban crashes and 9% of bicyclist rural crashes occurred in an intersection. In Boulder, 30% of fatal urban crashes and 6% of fatal rural crashes occurred in an intersection [19]. Intersections are usually more prevalent in urban areas, which are also more likely to have more complicated and larger intersections and could correlate to the larger percentages of bicycle crashes in urban areas.

## Virtual Reality and Simulators

Virtual Reality (VR) is a three-dimensional simulated environment that is built using computer modeling. It requires the use of a headset, controllers or gloves, and in some cases a body suit to allow individuals to interact with the artificial environment visually, audibly, and physically. Ihemedu-Steinke et al. (2017) found that for VR simulators with transportation applications, it is important to include high quality visual assets for vehicles and traffic models to create a believable environment. These traffic models should have all the components of a real traffic situation, like vehicles with drivers, traffic lights, traffic signs, landscape, pedestrians, and 1:1 mapping of motions to allow the driver to have the correct reaction cues [20]. However, there are some limitations with VR. One of these limitations is VR sickness. In humans, information from vestibular, visual, and proprioceptive senses is used to naturally understand motion in space. VR can cause conflicting information within these senses and lead to motion sickness. The frequency of VR sickness and onset time can be limited by minimizing the display time delay, reducing image flicker, increasing frame rate, decreasing field of view, decreasing depth of field, choosing the best display type, reducing duration, and increasing controllability (i.e., being able to actively control what is going on) [21].

VR simulations are commonly used to evaluate driver behavior. Taheri et al. (2017), for example, used a VR driving simulator to measure the driver's head movement, speed control, position of the vehicle, and control of the vehicle [22]. Road structure played a major role in whether drivers could maintain speed while in the VR simulator [22]. In contrast, Matthews et al. (1998) used a questionnaire to assess drivers' stress relative to performance in a driving simulator. They found that a habitual dislike of driving was associated with reduced control skills, greater caution, and disturbance of moods. A measure of aggressive driving predicted more frequent and more error-prone overtaking. They also predicted the speed of the driver's reaction to pedestrian hazards using an alertness measure [23].

Scott-Deeter et al. (2023) developed a study where 40 participants were put in 24 different intersection transversal scenarios in a bicycle simulator [24]. The goal of their study was to analyze how three different intersection treatments influence a cyclist's comfort, level of stress, and riding behavior. They used the ASL Mobile Eye XG platform for eye tracking and the galvanic skin response sensor to assess stress. The mixing zone treatment, which is when the vehicle is required to yield to the cyclist, caused the most discomfort of all of them. The bicycle signal treatment was the most comfortable [24].

Murano et al. (2009) conducted an experiment using a more advanced VR driving simulator that consisted of a vehicle cabin with a dome on a turntable, a 6 degree of freedom hexapod system, vertical vibration actuators, and a motion system capable of moving 35 meters longitudinal and 20 meters laterally [25]. The system can project images onto a 360-degree spherical screen surrounding the vehicle cabin.  It was built to reproduce near miss scenarios that are too dangerous to reproduce in real traffic. Murano indicated that a similar bicycle simulator could be implemented later to get a more accurate feel of cycling in different environments and improve on the analysis [25].

## Bicycle-Detecting Automatic Emergency Braking

Bicycle detecting automatic emergency braking (AEB) system is an advanced driver assistance system (ADAS) designed to automatically apply the brakes when it detects an imminent collision with a bicycle. The system works by using sensors to detect a bicyclist in the path of the vehicle and apply brakes to prevent or lower the severity of a vehicle-bicycle crash. Haus et al. (2021) mentioned that there are many factors that affect the effectiveness of AEB systems. Some factors include time of detection, time requirements for braking, the effects of pavement conditions on maximum possible braking, and the effects of obstructions [26]. Kullgren et al. (2022) found that bicycle detecting AEB could be effective in reducing the overall injury crash risk by 21%. In rain, fog, and snow conditions there was a 53% reduction, in low-speed conditions there was a 15% reduction, and in high-speed conditions there was a 26% reduction in injury crashes [27].

The Euro NCAP has developed a few tests to evaluate bicycle-detecting AEB. These tests include a vehicle approaching a crossing path with cyclist, turning across the path of a cyclist, approaching a crossing path with a cyclist behind a parked vehicle, and bicycle detection when a vehicle is approaching a cyclist along the roadside. For cycle crossing path, the cyclist is traveling either 15 km/h or 20 km/h depending on whether the cyclist is approaching from the near or far side (Figure 1 - Figure 2). In these situations, the vehicle travels 10 km/h to 60 km/h by 5 km/h increments. In the vehicle turning across path of cyclist case, the cyclist travels 15 km/h and the vehicle travels between 10 km/h and 20 km/h by 5 km/h increments depending on whether the cyclist is approaching from the near or far side. When the vehicle is approaching a crossing path with cyclist traveling from behind a parked vehicle, the cyclist is traveling at 10 km/h and the vehicle is traveling between 10 km/h and 60 km/h by 5 km/h increments (Figure 3). For each of the crossing path tests, the impact is staged to occur at 50% of the width of the vehicle. For the vehicle approaching a cyclist along the roadside, there are two tests. The first is when the impact location is 50% of the vehicle's width. In this case, the cyclist is traveling at 15 km/h and the vehicle is traveling between 25 km/h and 60 km/h by 5 km/h increments (Figure 4). In the second test, the impact location is 25% of the vehicle's width. The bicyclist travels 20 km/h and the vehicle travels between 50 km/h and 80 km/h by 5 km/h increments (Figure 5) [28].

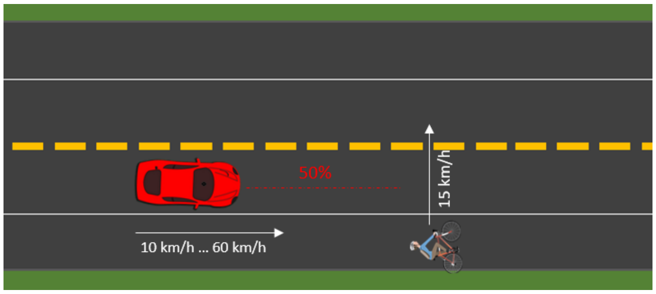


**Figure 1. Euro NCAP Testing Diagram: Straight crossing path from near side.**

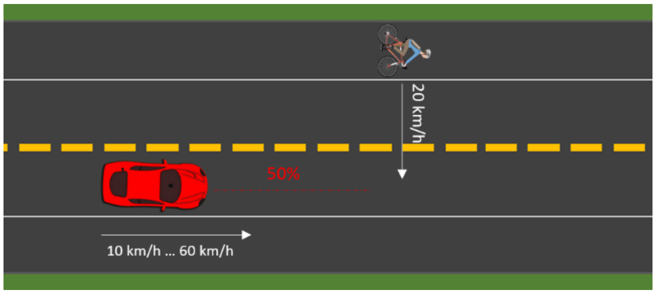


**Figure 2. Euro NCAP Testing Diagram: Straight crossing paths from far side.**

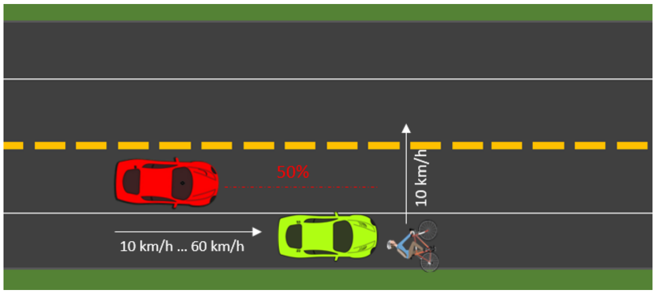


**Figure 3. Euro NCAP Testing Diagram: Crossing paths with cyclist approach from behind a parked vehicle.**

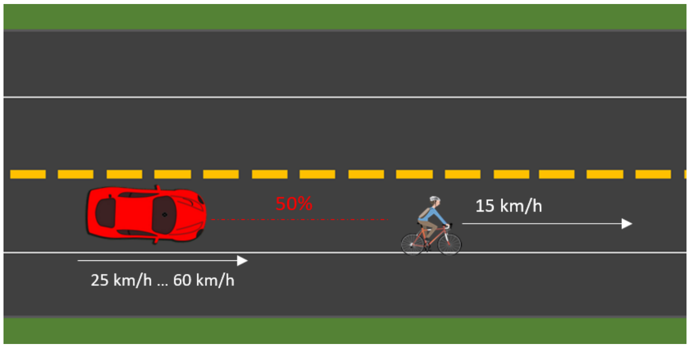


**Figure 4. Euro NCAP Testing Diagram: Parallel paths with cyclist at 50% impact location.**

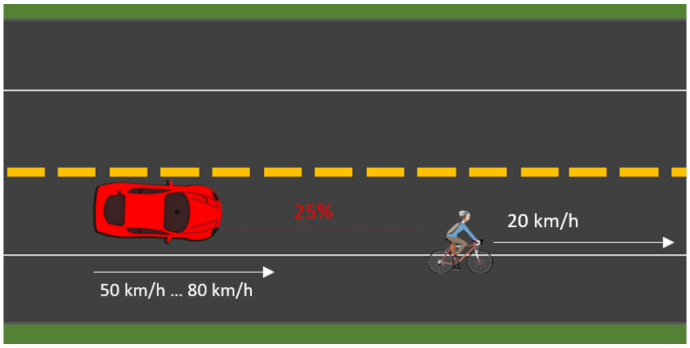


**Figure 5. Euro NCAP Testing Diagram: Parallel paths with cyclist at 25% impact location.**

## Purpose Statement

The purpose of this study is to characterize bicyclist behavior, as they interact with vehicles, to improve the crash avoidance potential of ADAS and improve the overall safety implementations for cyclists. In this thesis, an analysis was conducted to determine scenarios to test how bicyclists interact with vehicles on roadways using VR. VR testing was then conducted, and bicyclist dynamics were captured and analyzed.

# Chapter 2: Bicycle Crash Scenario Development

## Introduction

With increasing bicycle use, there has been an increase in reported crashes involving bicyclists [29]. However, the crashes between cyclists and vehicles often go unreported [8]. This presents a challenge for understanding the full nature of crashes that involve a bicyclist, which is essential for their reduction. Key elements include how these vehicle crashes with cyclists occur, the locations where these crashes occur, and what causes them. The purpose of this chapter was to identify real-world fatal vehicle-bicycle crash scenarios for relevant participant testing in VR to further understand cyclist behavior.

## Methods

### Data Source

The data used in this study was taken from the Fatal Analysis Reporting System (FARS). FARS annually reports all crashes that involve at least one fatality and describes basic crash information based on the police report, such as age, sex, speed, drug use, and time of day. The data selected for this study was from the accident, vehicle, safety, and pbtype tables. The data was separated to include only fatal crashes that involved a bicyclist by grouping the data by case key and filtering to include all crashes that involved the variable per_type or pbptype equal to six. FARS provides additional data on bicycle and pedestrian fatal crashes in the pbtype table. The pbtype dataset includes data such as the crash type, location of the cyclist, and the direction the cyclist was traveling. The pbtype dataset began collection in 2014, therefore, the analysis was limited to years 2014 to 2020, where 2020 was the most recent year available. From this dataset, crashes were characterized by the cyclists' sex, the cyclists' age, the crash type, the direction the bicyclists were traveling relative to the vehicle, the bicyclists' location, alcohol use, drug use, helmet use, lighting conditions, time of day, month, state, drivers' age, drivers' sex, type of vehicles involved in the crash, speed limit, road type, and urban versus rural areas.

**Case Selection**

The following table shows the number of total fatal crashes, total vehicle involved in a fatal crash, total number of individuals involved in a fatal crash, and fatally injured individuals based on the selection criteria. The selection criteria involve the total number of fatal crashes between 2014 and 2020, then the number of those crashes that involved at least one bicyclist. The bottom two rows are the number of drivers and bicyclists involved in a fatal bicyclist crash.

**Table 1. Case selection criteria for analysis of fatal bicyclist and driver characteristics in crashes involving at least one bicyclist.**

| Selection Criteria | Crashes | Vehicles | All Individuals | Fatally Injured |
|---|---|---|---|---|
| FARS 2014 to 2020 | 234,831 | 358,081 | 581,752 | 255,262 |
| Involved at least one bicyclist | 5,862 | 6,220 | 14,094 | 5,919 |
| Drivers | 5,861 | 6,220 | 6,220 | 48 |
| Bicyclists | 5,862 | 0 | 6,064 | 5,908 |

**Characterization and Scenario Development**

Case year, sex, age, state, direction the cyclist was traveling, if the cyclist was in an intersection or not, location on the road, bike lane or sidewalk, pre-crash event, crash type, drug use, alcohol use, helmet use, lighting conditions, time of day, and month were the variables used to complete the analysis. These variables were selected due to their availability and suitability towards the development of test scenarios. The direction the cyclist was traveling, if the cyclist was in an intersection or not, location with respect to bike lane or sidewalk, pre-crash event, and crash type were considered the most important variables in terms of developing scenarios. The top scenarios were chosen based on the prevalence of fatally injured cyclists within the mentioned categories.

# Results

## Bicycle Crash Characterization

Fatal bicycle crashes increased from 2014 to 2020 (Figure 6). In 2014, there were 741 fatally injured cyclists and in 2020 there were 932 fatally injured cyclists, a 26% increase. Most (86.3%) fatally injured bicyclists were male and 13.2% were female (Figure 6). This may in part be due to the fact that there are more male cyclists than female cyclists [30].

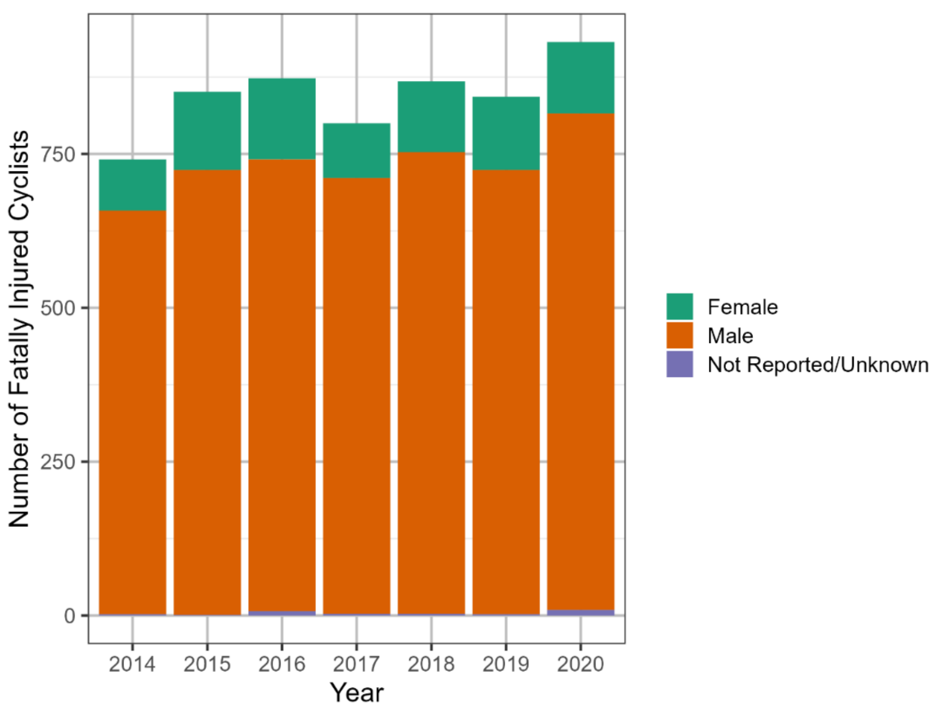



**Figure 6. Number of fatally injured bicyclists from 2014 to 2020.**

The median age of fatally injured cyclists was 50-years-old. After 12-years-old there is an increase in fatally injured cyclists. There is another increase in frequency around 50- to 65-years-old (Figure 7).

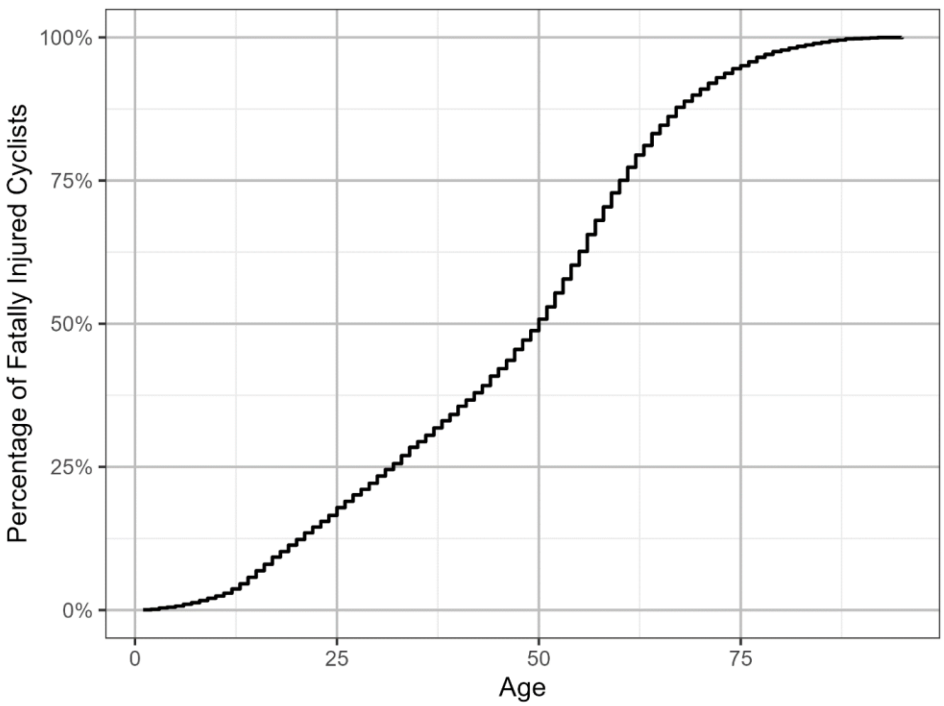



**Figure 7. Age of fatally injured bicyclists**

Florida and California have the most fatal crashes (Appendix A). This could be due to the high population of these states and the larger number of bicyclists based on conditions like the weather, traffic density, and vehicle parking availability.

In 65.3% of the fatalities, the cyclists were traveling in the same direction as traffic. Only 15.8% of fatally injured cyclists were traveling against traffic (Figure 8).

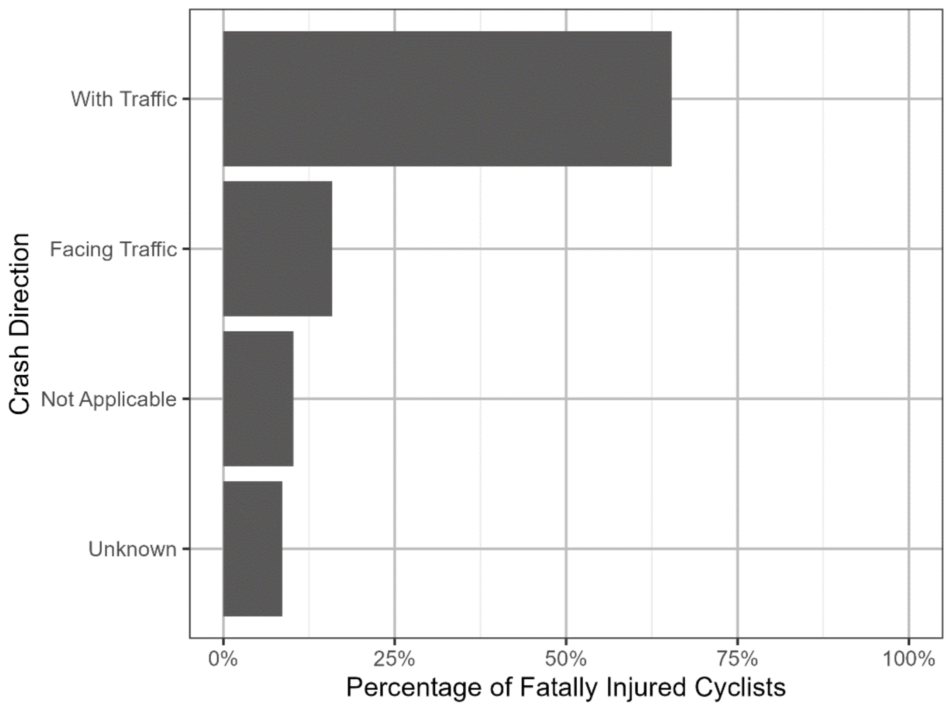



**Figure 8. Direction the bicyclists were traveling with respect to the vehicle involved in the fatal crash.**

The majority (62.6%) of the fatally injured cyclists were not at an intersection (Figure 9). Only 28.4% of the fatally injured cyclists were in an intersection, and 8.2% were in an area that is classified as intersection-related (Figure 9). Intersection related is defined as being in a trafficway and within 50 feet from an intersection or related to the flow of traffic through an intersection.

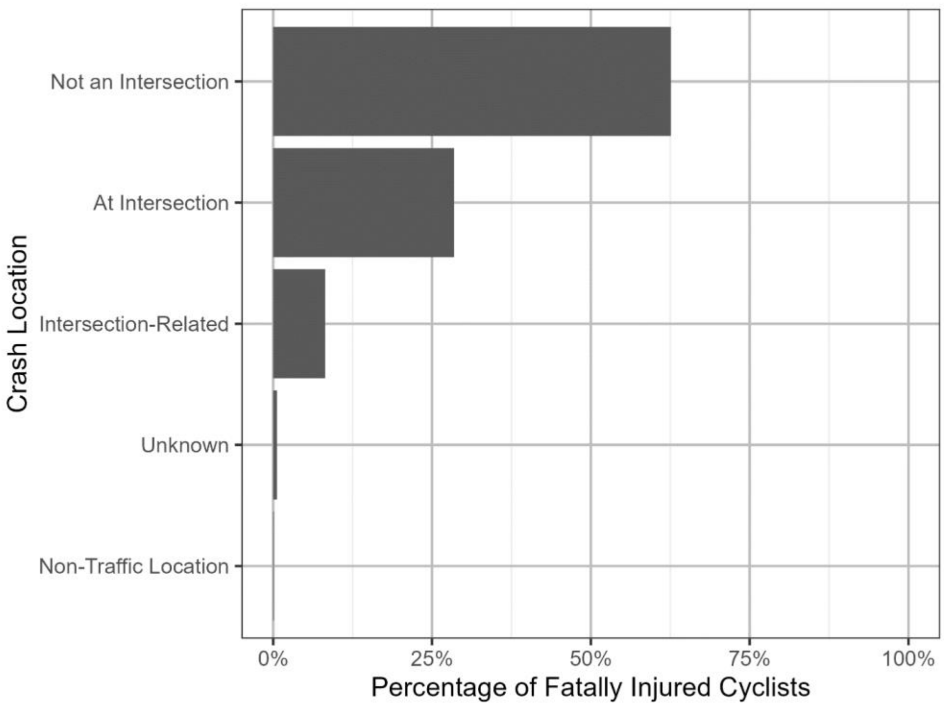



**Figure 9. Proportion of fatally injured bicyclist in intersection.**

The travel lane was the most common location (78.3%) at which a cyclist was fatally injured, followed by sidewalk/crosswalk/driveway access at 11% and bike lane/paved shoulder/park lane at 8% (Figure 10).

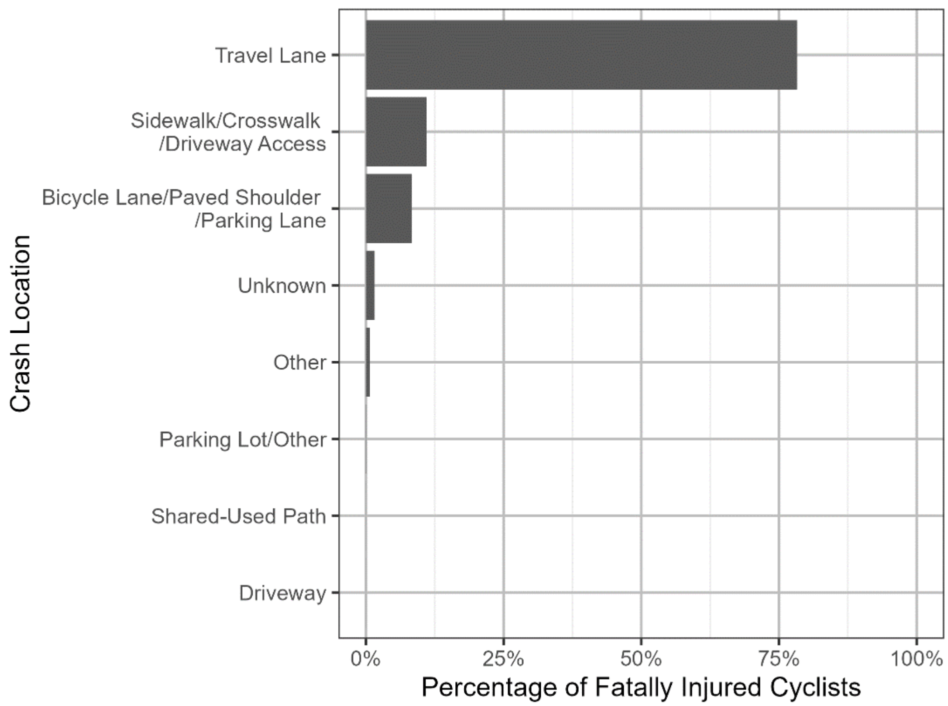



**Figure 10. Location (bike lane, sidewalk, etc.) of fatal bicycle crashes.**

Overtaking is defined as approaching from behind at a faster speed and performing a passing maneuver. Motorists overtaking a bicyclist was the most common scenario of these fatal crashes, where 29.5% of the cyclists were fatally injured. The second leading cause of fatal crashes was bicyclists failing to yield. All types of bicyclist failures to yield accounted for 14.5 % of fatally injured cyclists (Figure 11 - Figure 12).

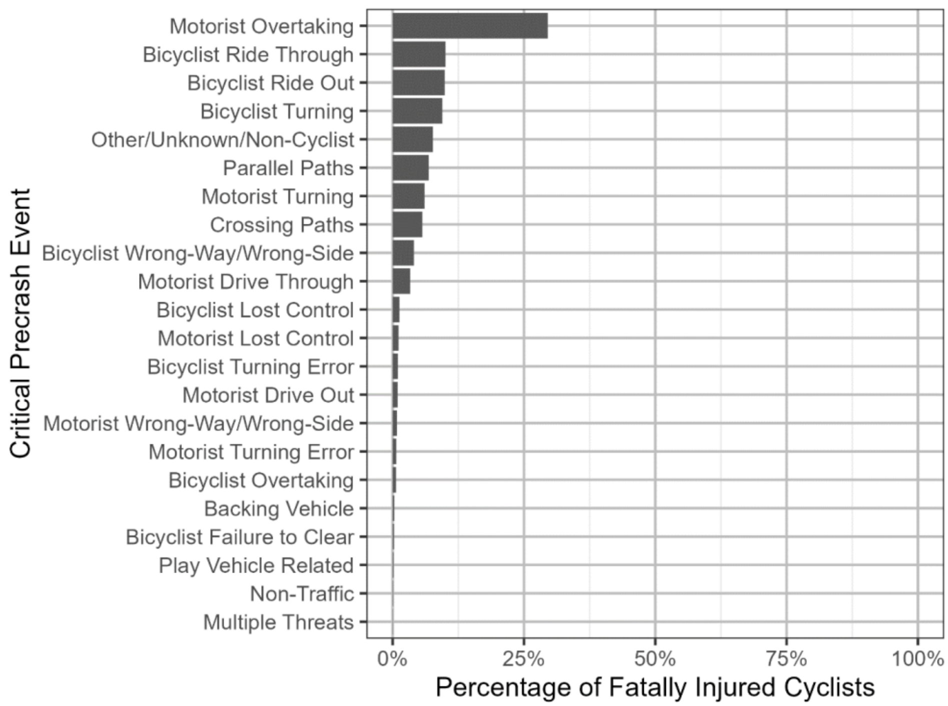



**Figure 11. Type of critical bicyclist pre-crash events (Fatal Crashes).**

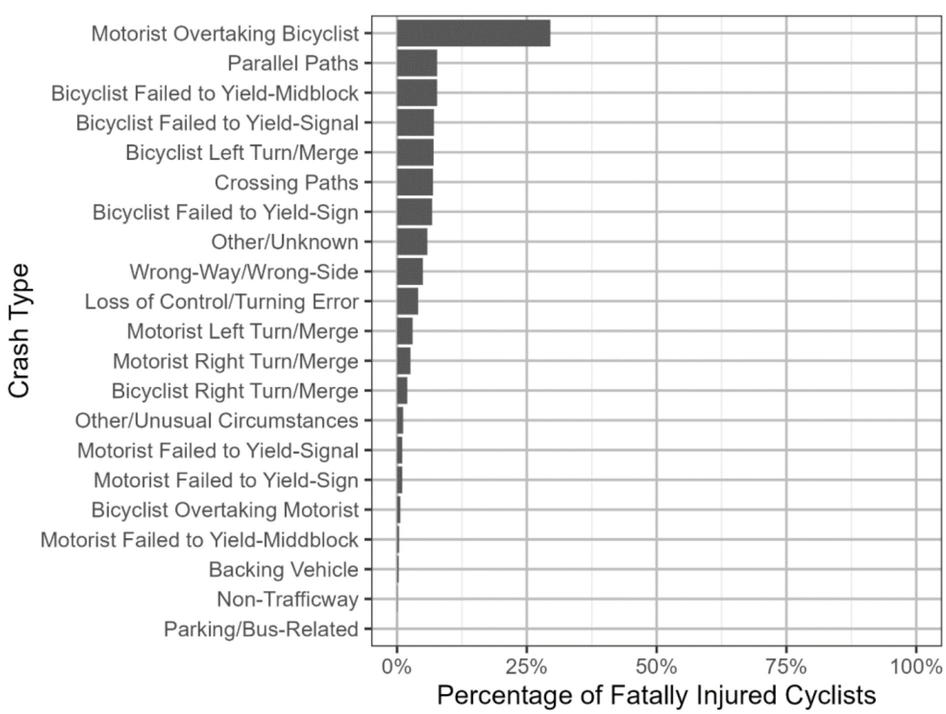



**Figure 12. Bicyclist crash types (Fatal Crashes)**

In fatal bicycle crashes, most fatally injured cyclists were reported as not under the influence of drugs or alcohol. Drug use among fatally injured cyclists was 7.7% and alcohol use among fatally injured cyclists was 9.6% (Figure 13 - Figure 14). Not reported/unknown corresponds to the individuals that were not tested after the crash.

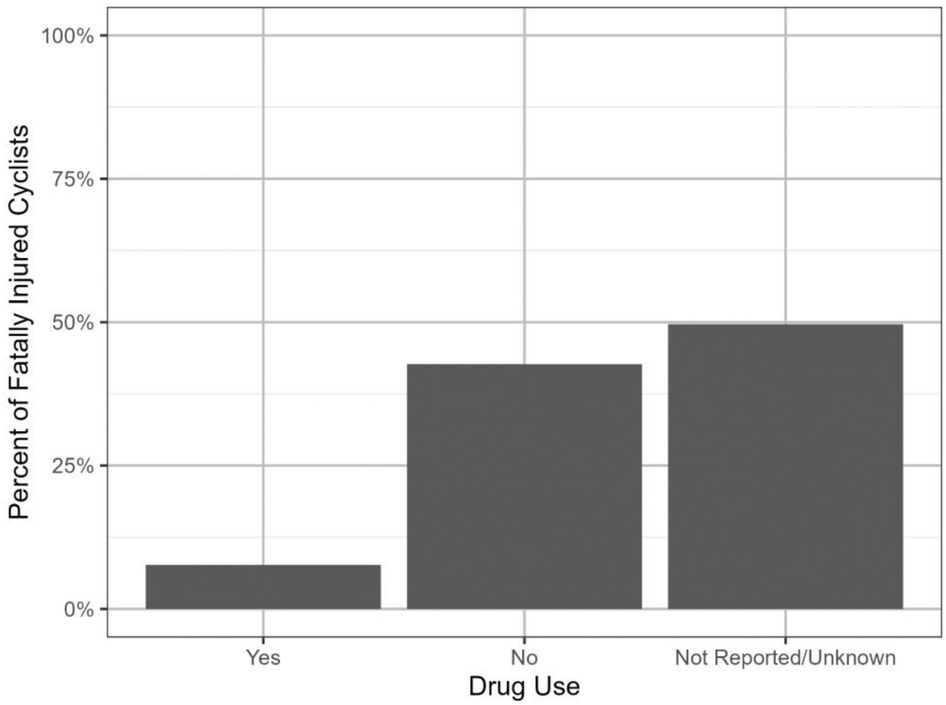



**Figure 13. Fatally injured bicyclists with respect to drug use.**

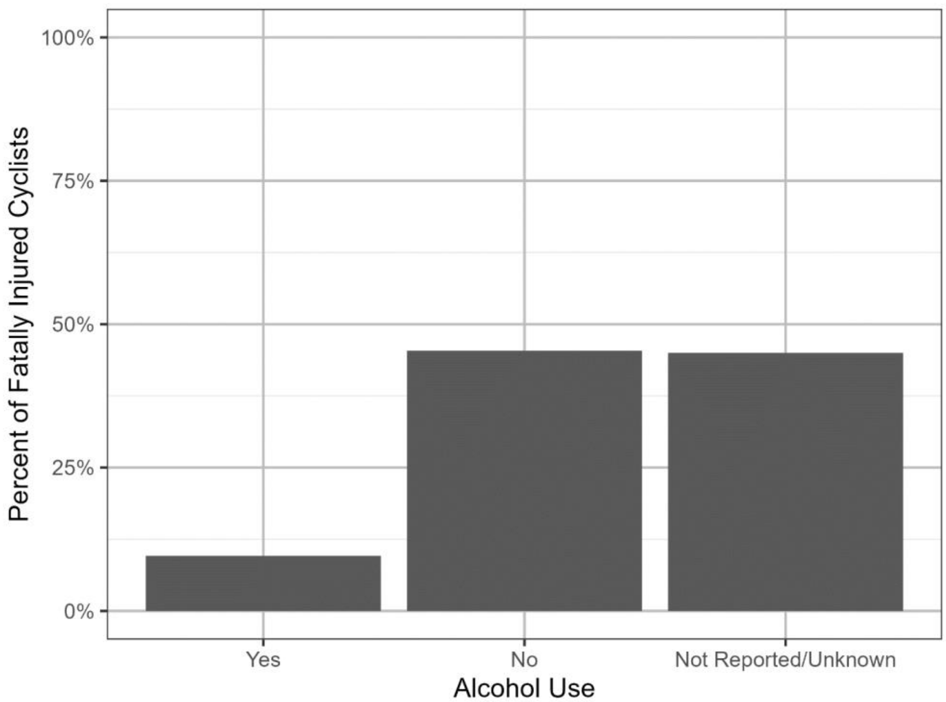



**Figure 14. Fatally injured bicyclists with respect to alcohol use.**

The majority (58.8%) of fatally injured cyclists were reported as not wearing a helmet (Figure 15). This could be a result of helmets lowering the severity of these crashes for cyclists who wear them by reducing head impact forces.

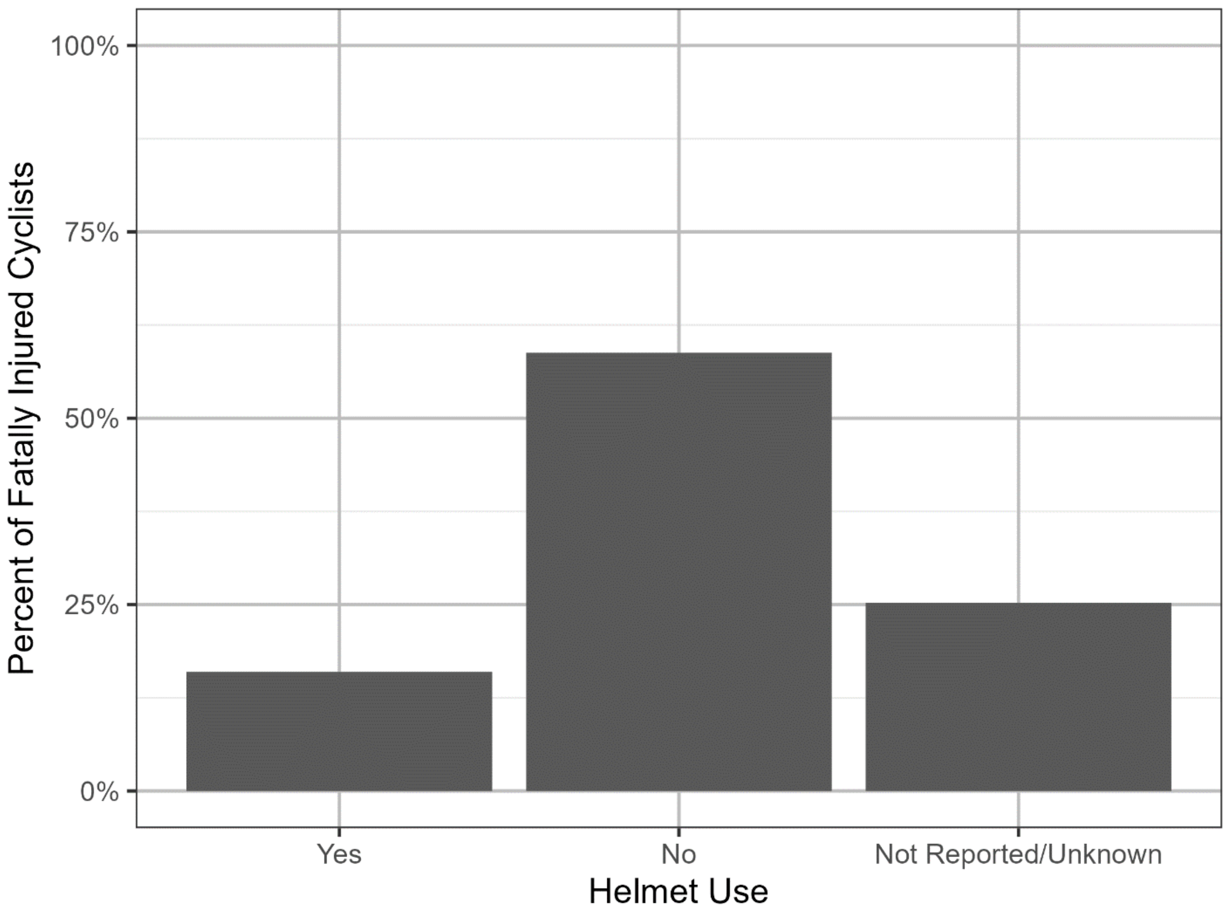



**Figure 15. Fatally injured cyclists with respect to helmet use.**

The largest percentage of fatal bicycle crashes occur when it is light and during the warmer months of the year (Figure 16, Figure 17, Figure 18). This could be a result of cyclists preferring to ride in warmer weather and during times of higher visibility.

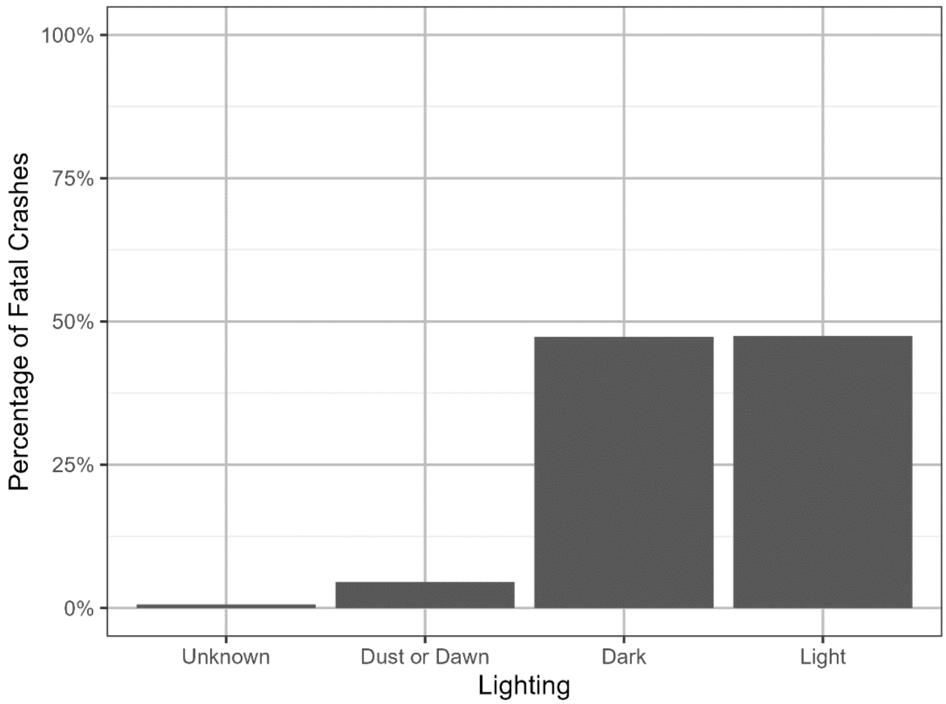



**Figure 16. Percent of Fatal Bicycle Crashes Based on Lighting Conditions.**

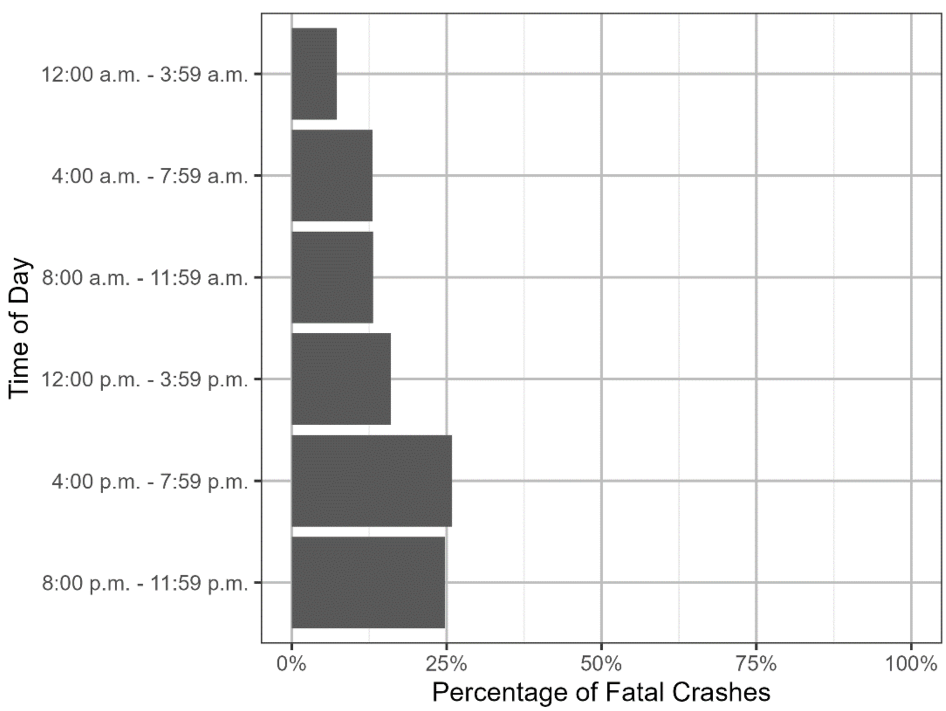



**Figure 17. Percent of Fatal Bicycle Crashes with Respect to Time of Day.**

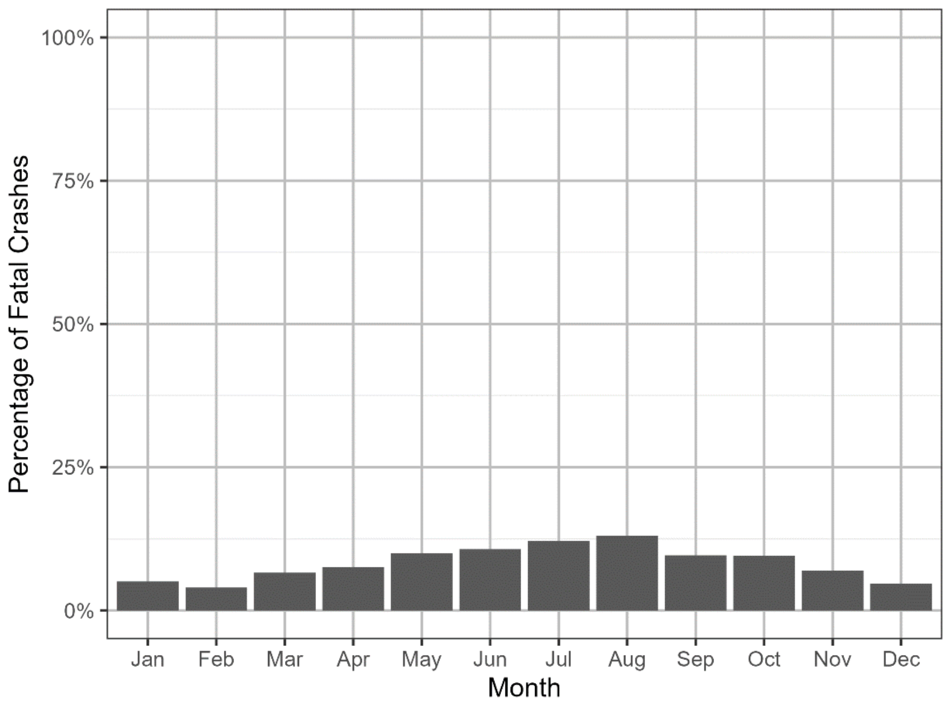



**Figure 18. Fatal Bicycle Crashes with Respect to Month.**

### Driver Characteristics

The majority of drivers involved in a fatal crash with a cyclist were between 18 and 30. The median age was 38 years old (Figure 19). The majority were also male (64.7%) (Figure 20).

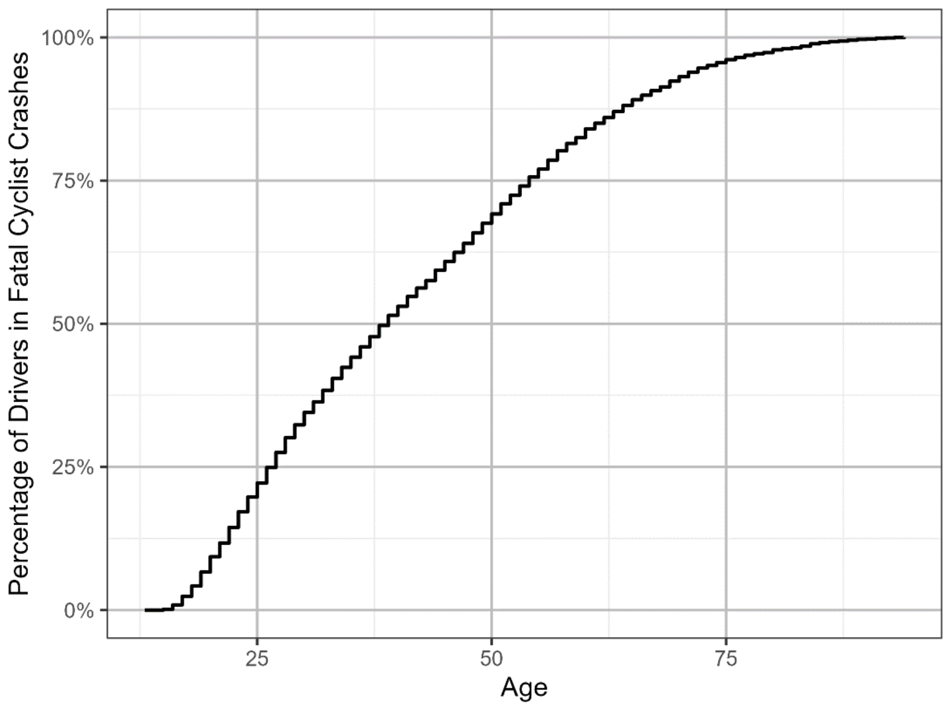



**Figure 19. Age of driver involved in fatal bicycle crash.**

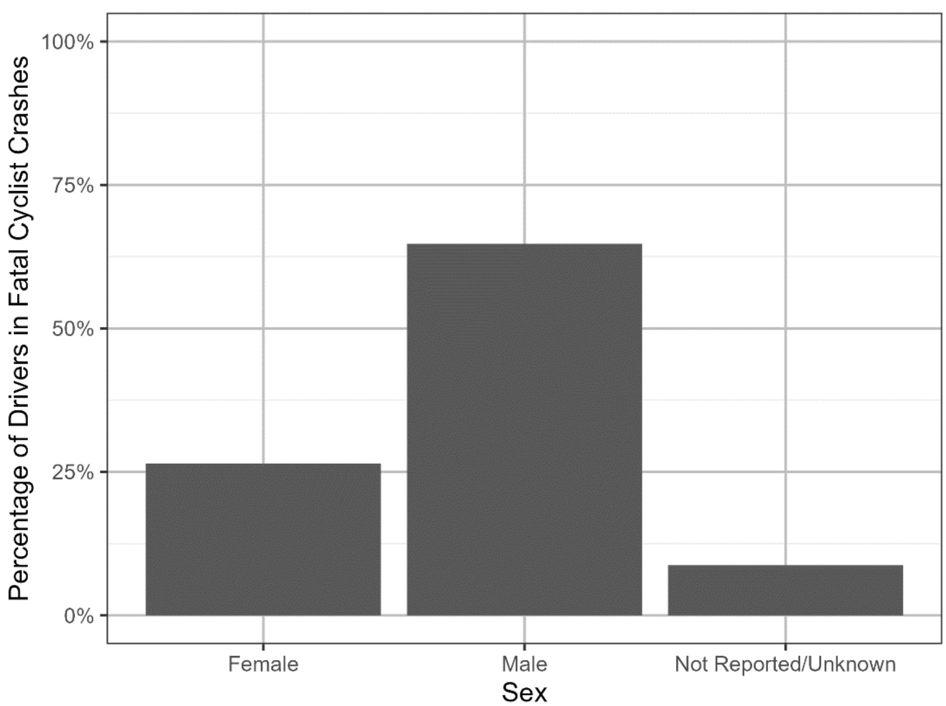



**Figure 20. Sex of driver involved in fatal bicycle crash.**

Rarely were the drivers impaired by drugs (4.8%) or alcohol (8.2%) when involved in a fatal bicycle crash (Figure 21 - Figure 22).

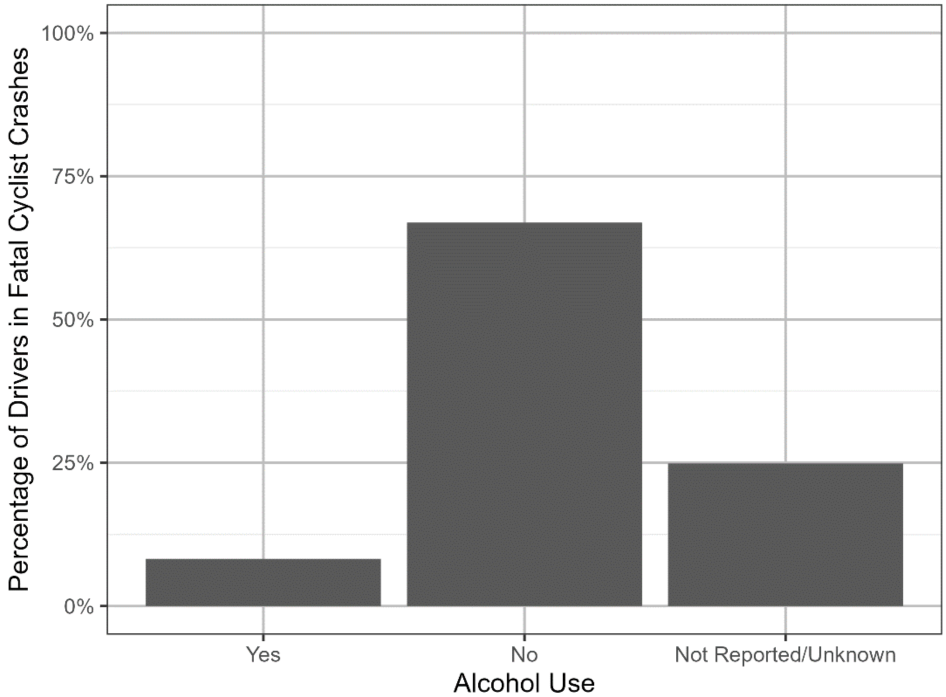



**Figure 21. Percentage of drivers that were involved in a fatal bicycle crash that used alcohol.**

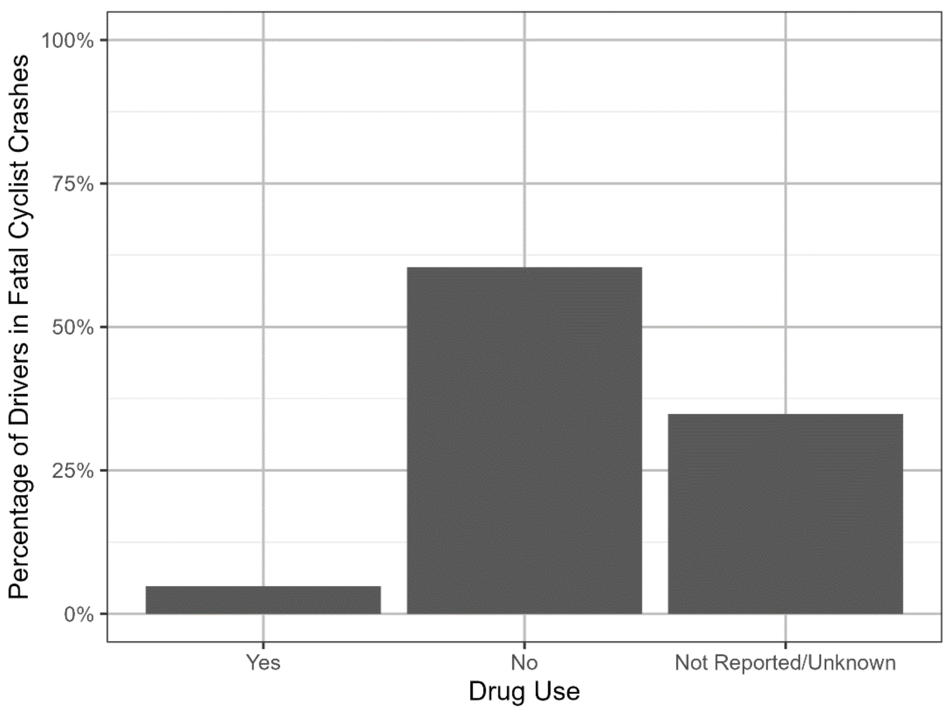



**Figure 22. Percentage of drivers that used drugs when involved in a fatal crash with a bicyclist.**

The majority of fatal bicycle crashes were with passenger vehicles (35.3 %), SUVs (18.5 %), and small trucks (17.4 %) (Figure 23). They also occurred mostly when the speed limit was 45 mph (20.9%), 35 mph (18.5%), and 55 mph (17%) (Figure 24).

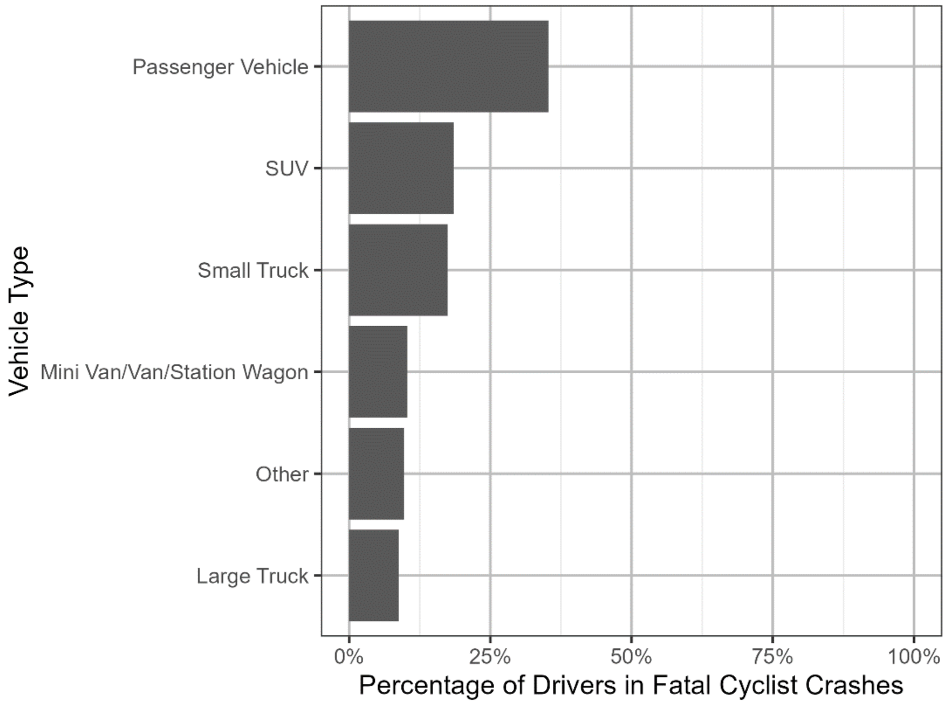



**Figure 23. Percentage of Vehicle Types Involve in Fatal Bicycle Crashes.**

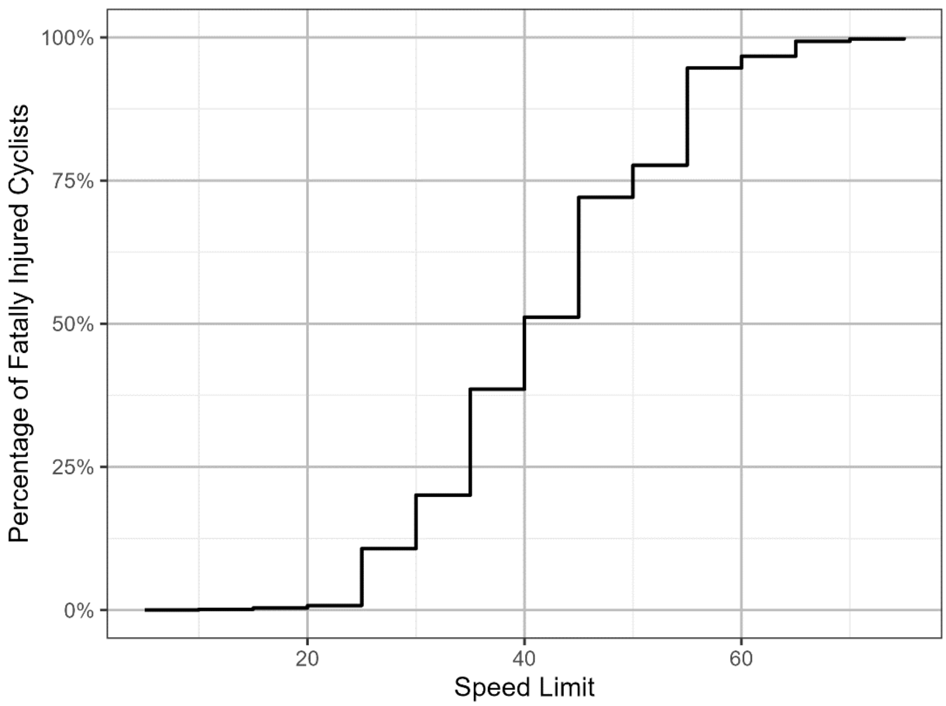



**Figure 24. Speed Limit When Cyclist was Involved in a Fatal Crash.**

The majority of crashes occurred in urban areas (76.4 %), on two lane roads (56.3%), and when the road type was either two-lane undivided (65.%) or two-lane divided (29%) (Figure 25, Figure 26, Figure 27).

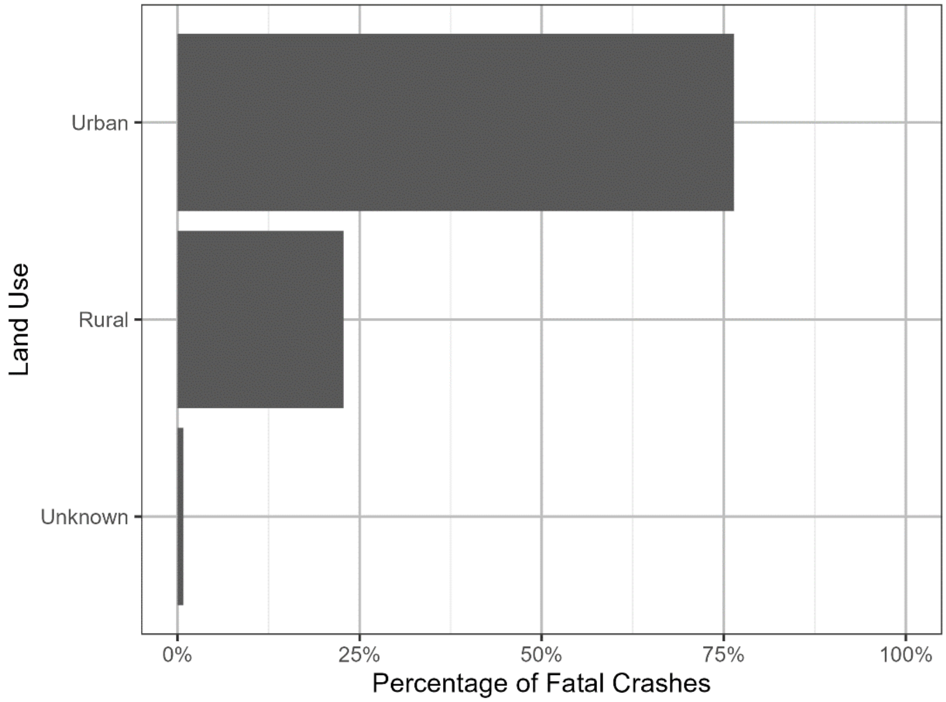



**Figure 25. Percentage of Crashes That Were Either in Rural or Urban Areas.**

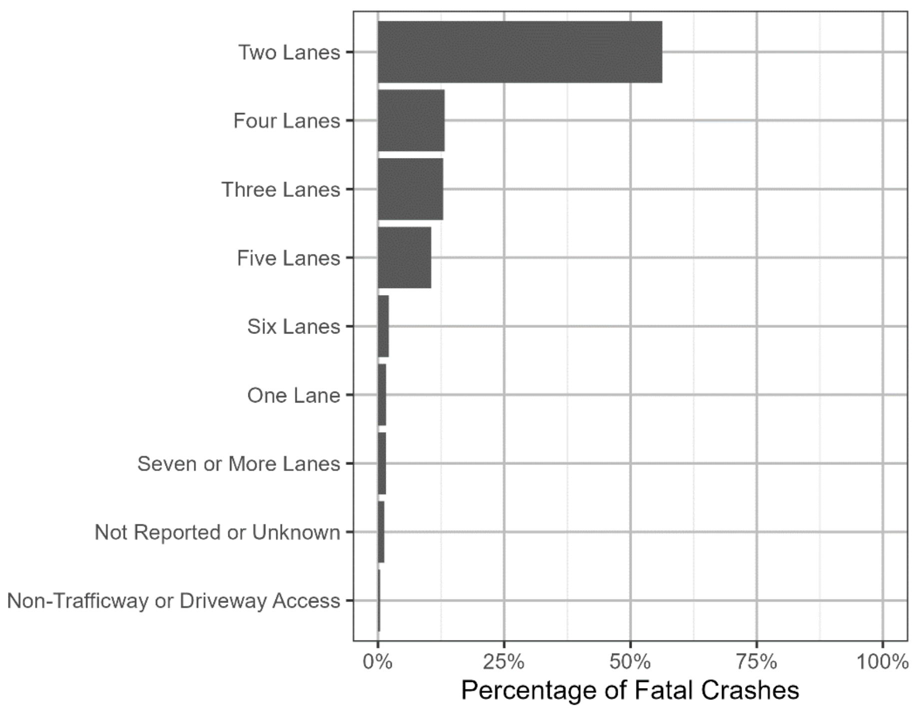



**Figure 26. Number of Road Lanes When a Cyclist was Involved in a Fatal Crash.**

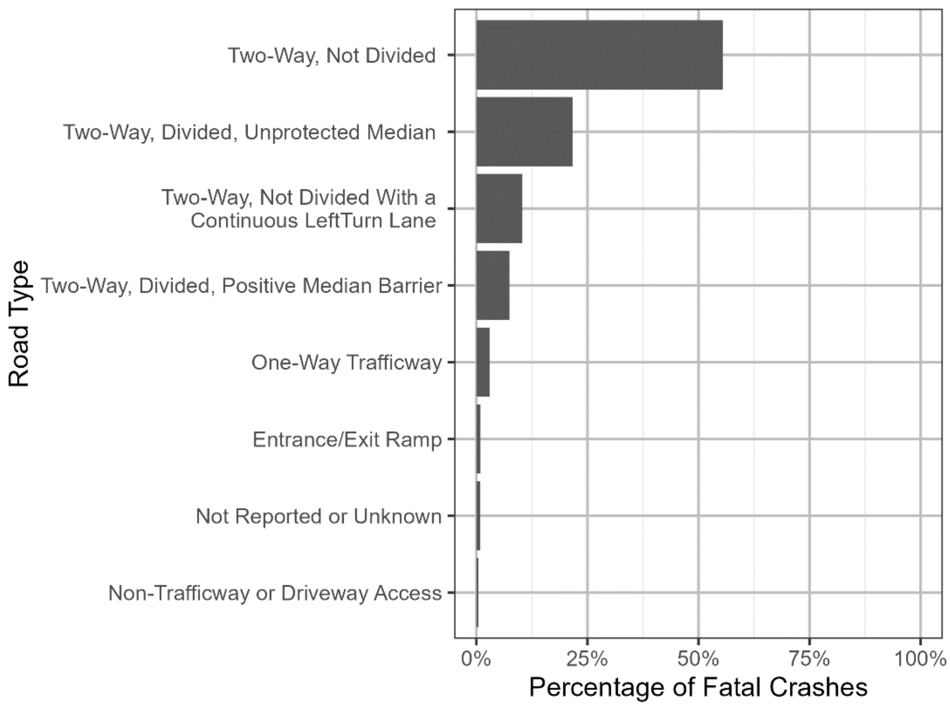



**Figure 27. Road Type When a Cyclist was Involved in a Fatal Crash.**

## Bicycle Crash Scenarios

To select the best scenarios for testing, a few factors had to be considered, including (1) what what the crash types that occurred most often, (2) how often did the combination of each of the most common variables occur, and (3) what can be feasibly developed in a VR environment to allow for a realistic feel. Table 2 shows the most common pre-crash event in the scenario column. The fit column includes cases where the lighting condition was "light," the rider was transversing a 2-lane road that was two-way and undivided, the vehicle was a passenger vehicle, and the cyclist was traveling in the travel lane with traffic. Scenarios that differed from this specific situation are recorded in the subsequent columns. Differing lighting included dark, dusk, and dawn. Lane differences included any other number of lanes other than 2 and any other road type other than 2-ways undivided. Vehicle differences included every other vehicle type (i.e., SUVs, vans, small trucks, and large trucks). Travel direction differences included anything other than traveling in the travel lane with traffic. Differences were determined one at a time, for example, cases in the lighting difference columns would still match the number of lanes, vehicle type, and travel direction in the "Fit" column.

**Table 2. Combinations for scenario selection.**

| Scenarios | Fit | Lighting Difference | Lane Difference | Vehicle Difference | Travel Direction Difference | Total |
|---|---|---|---|---|---|---|
| Vehicle Overtaking / Parallel Paths (Main Scenarios) | 99 (1.68%) | 171 (2.89%) | 17 (0.29%) | 267 (4.52%) | 36 (0.61%) | 2,202 (37.3%) |
| Straight Crossing Path | 2 (0.03%) | 4 (0.07%) | 1 (0.02%) | 1 (0.02%) | 3 (0.05%) | 410 (6.94%) |
| Cyclist Fail to Yield | 25 (0.42%) | 15 (0.25%) | 11 (0.19%) | 48 (0.81%) | 3 (0.05%) | 1,277 (21.6%) |
| Other | 77 (1.3%) | 75 (1.27%) | 19 (0.32%) | 186 (3.15%) | 23 (0.39%) | 2,019 (34.2%) |
| Total | 203 (3.44%) | 190 (3.22%) | 48 (0.81%) | 454 (7.68%) | 62 (1.05%) | 5,908 (100%) |

From the analysis, scenarios were developed for subsequent analysis of cyclists' behavior. The first scenario was an overtaking scenario with the cyclist traveling in the same direction as traffic when not in a bicycle lane (Figure 28). This scenario of motorists overtaking bicyclists was by far the most common crash type among fatal cyclist crashes. Cyclists traveling in the direction of traffic when not in a bike lane was also the most common of the crash locations with respect to bike lane, and sidewalk (Figure 10 - Figure 12). The second, third and fourth scenarios were variations of the first to include a bike lane, shoulder, and both a bike lane and a shoulder. This manipulation allowed analysis of behavior differences due to the inclusion of each of these infrastructure features (Figure 29).

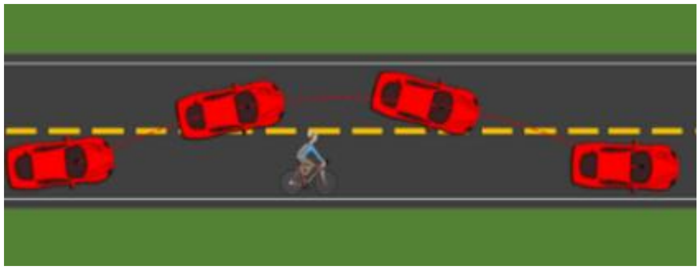


**Figure 28. The cyclist traveling in the same direction as traffic, and not given a bicycle lane.**

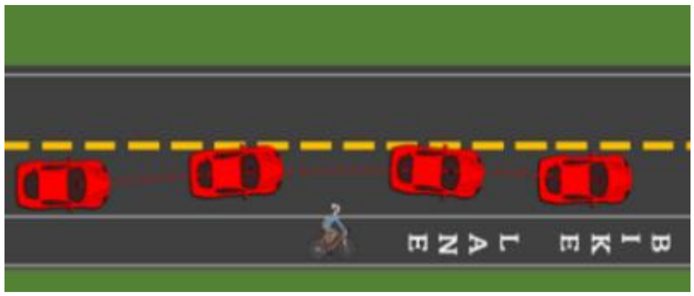



**Figure 29. The cyclist traveling in the same direction as traffic and given a bicycle lane.**

The last scenario would be how cyclists would interact in an intersection (Figure 30). In this scenario, the vehicle and cyclist will each travel straight crossing paths in the intersection. This is based on intersection crashes being a common crash location (Figure 9). Although the scenario was considered due to its prevalence in fatal crashes, it was excluded from further participant testing. Incorporating this scenario and its potential variations into the development of the VR environment introduced significant complexities and the intended goal of this effort was only an initial testing of bicyclists' behavior in one set of scenarios.

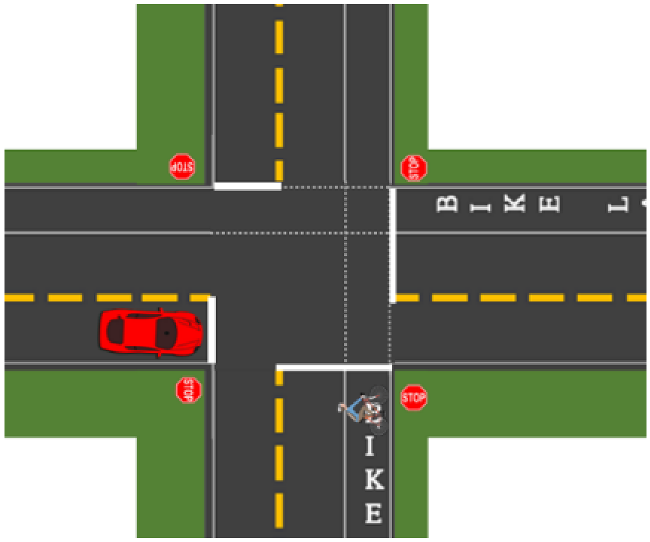


**Figure 30. The cyclist meeting a vehicle in an intersection.**

## Discussion

Most fatal bicycle crashes were caused by motorists overtaking cyclists and most of these crashes happen in a travel lane where the bicyclist is traveling in the direction of traffic. Most of the crashes also occur in places with a high population density and frequent good weather. Furthermore, the victims of the crashes are usually 50- to 65-year-old and male. This information was used to construct scenarios capturing the most common fatal bicycle crash scenarios.

The results from this FARS analysis portion correlated directly to previous research. For example, the most fatal crashes occurred when a vehicle performed an overtaking maneuver [10]. Increases in crashes involving cyclists were also observed, along with a prevalence of male and older individuals in fatally injured cyclists [3][4]. The majority of crashes also occurred in urban areas [3].

To capture the most common fatally injured cyclists, the main focuses should be on the direction and the location the cyclists are traveling and how they interact with vehicles. A scenario can include a cyclist traveling on the road in the same direction as traffic and they are being approached from behind by a vehicle. The goal in this scenario could be to see how the cyclist responds to a vehicle performing an overtaking maneuver.

Indeed, the Euro NCAP does three tests that incorporate the cyclist crossing the path of the vehicle and two tests where the cyclist is traveling along the same path as the vehicle to test cyclist detection for AEB [31]. These scenarios include a vehicle approaching a crossing path with a cyclist, a vehicle turning across the path of a cyclist, a vehicle approaching a crossing path with a cyclist behind a parked vehicle, and bicycle detection when a vehicle is approaching a cyclist along the roadside. These tests are similar to the scenarios developed for this thesis work. The first scenario and its variants were the same as the vehicle approaching the cyclist along the roadside in terms of the configuration of the vehicle and cyclist traveling in the same direction. It differed in terms of the 50% and 25% overlap/impact location, since there was no impact in any of the scenarios to be modeled since the goal was to observe how bicyclists behaved during overtaking situations. The last scenario is similar to the approaching at a crossing path test. The last scenario is set at an intersection which can be configured in different ways to incorporate the turning across path of a cyclist.

Some other things that need to be considered are bicyclist age, helmet use, time of day, lighting conditions, month of the year, and blood alcohol concentration. These all can play a role in how bicyclist behave and interact with vehicles. Also, the time of day that a majority of the crashes happened was between 6 and midnight based on IIHS data [32]. Based on the analysis done in FARS, the highest percentage of fatal crashes occurred when the lighting conditions were classified as light. Factors such as the time of year and location within the US, however, play a role in when the conditions are dark versus light. The highest percentage of fatal crashes also happen between June and August, which is usually when the weather is warmer and light hours are extended. Finally, about 25% of all bike crashes occurred when the cyclist was classified as legally drunk with a BAC of 0.08% of higher [33].

In the US, if the individual is over 17 then they are not required to wear a helmet [34]. While some states have no laws for helmet use (e.g., Virginia), individuals in other states are required to wear a helmet until a certain age. Helmet use results in less fatalities in crashes. When examining the difference in fatalities of the bicyclists that wore a helmet versus those that did not, there was a much larger number of fatalities for those who did not wear a helmet. Helmet use should be a requirement and enforced for cyclists no matter the age, in order to lower the fatality rate of cyclists. Future studies could investigate how cyclist behavior changes with and without a helmet to see if there is any difference that could correlate to the fatality rate.

**Limitations**

There are limitations to this analysis that need to be reiterated. This data includes only fatal crashes involving a bicyclist; non-fatal crashes where a cyclist may have only been injured or did not endure any injuries are not included. Therefore, the results of this study may not represent all bicycle crashes. Another limitation is that the dataset that was used is only from 2014 to 2020. The data did not include a large span of years that would provide a more accurate analysis on how bicyclist fatal crashes have changed over time.

# Chapter 3: VR Bicycle Simulations

## Purpose Statement

This chapter describes the construction of a VR environment, bicycle interface, and study design to characterize bicyclist behavior during overtaking scenarios across varied road infrastructures. This was done with the use of a bicycle simulator that consists of a VR headset and a stationary bike that allows the rider to navigate the VR environment.

## Environment

A VR environment was developed with the intention of immersing participants, causing them to respond similarly to how they would in reality while navigating through the world on a bicycle and experiencing each developed scenario. The VR environment was used to analyze bicyclist behavior over different road infrastructure in a randomized order using the Unity gaming engine platform. Unity was used because it is a popular gaming engine for VR development with vast developer support resources. The environment was composed of a 3,700-meter (2.3 mile) road. The road was composed of two undivided lanes with no intersections. Along the road, there were four different roadway designs including: (1) a road with a bike lane, (2) a road with a shoulder, (3) a road with both a bike lane and a shoulder, and (4) a road with neither a bike lane nor a shoulder. The roads were designed to have a width of 6 m (or about 3 meters per lane) from edge to edge not including any bike lane or shoulder [35]. The shoulder and bike lane, when present, were each 1.5 meters [36]. For each of the different road designs, there was 400 meters (0.25 miles) of straight road where vehicles performed an overtaking maneuver to pass the bicyclist. Three overtaking events occurred within each of these 400-meter stretches of road. The environment also include houses, stores, and other buildings to allow for a more realistic feel [20].

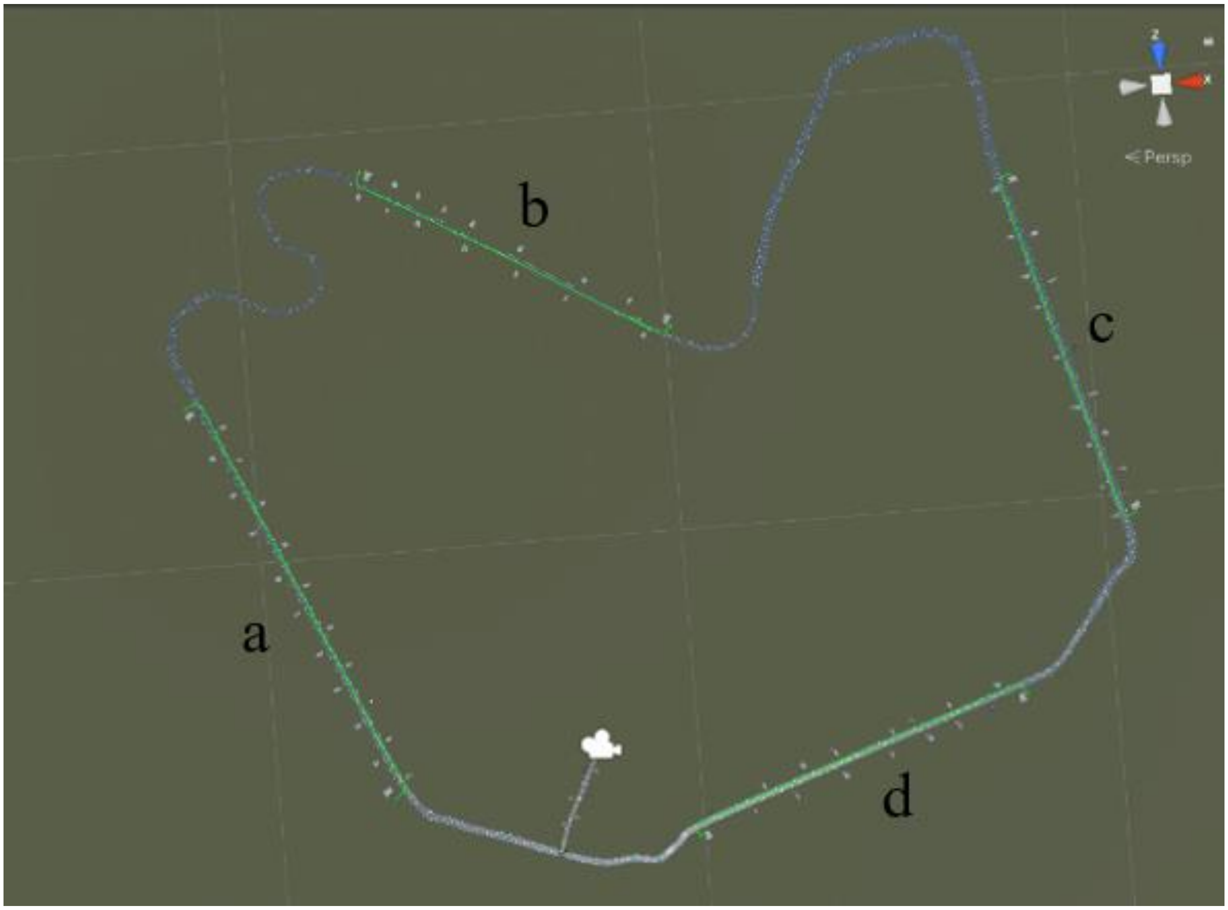



**Figure 31. Top view of the complete bike route. Segments a, b, c, d represent the 400-meter straight road segments where overtaking occurred.**

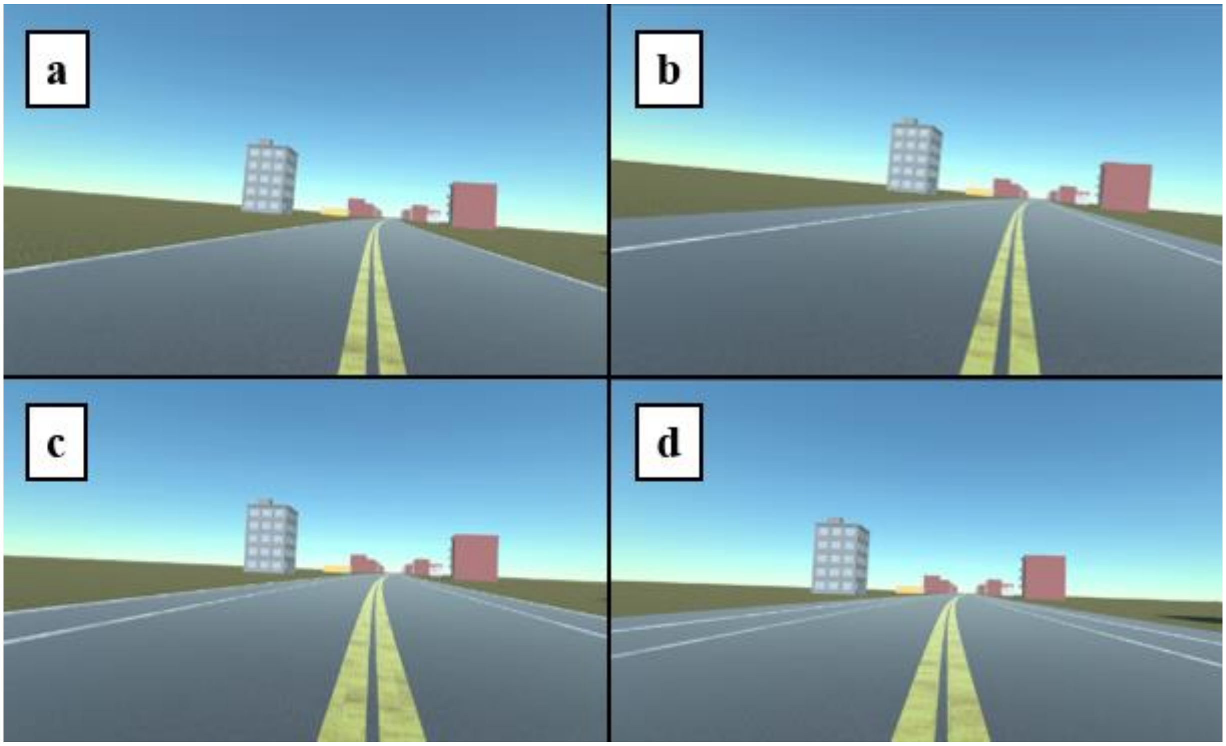



**Figure 32. The VR Road with (a) neither a shoulder nor a bike lane, (b) a shoulder, (c) a bike lane, (d) both a shoulder and a bike lane.**

## Interface

The participant in the study used an HTC VIVE Pro VR headset and a custom built stationary bicycle to interact with the VR environment. For the most realistic feel and to mitigate the possibility or VR sickness, the position and direction traveled were mapped 1:1 to the virtual environment [20].

The stationary bike allowed the participants to mimic real bicycle riding and translate the bicycle dynamics to the VR environment. It was designed to output speed, acceleration, roll, and steering angle signals to an Arduino processor, which then output the relative data to the Unity platform. The stationary bike consisted of a traditional bike mounted to a metal frame base to keep it stationary and a single longitudinal axis to allow the bike to roll. Four pistons that output 50 pounds of force each were attached from the metal frame base to the frame of the bike. Springs were aligned on the shaft of the front two pistons, allowing the cyclists to return to upright position. The rear piston shafts were reinforced with steel sheaths to keep the cyclists from rolling the bike past 10 degrees. The rear wheel also included a tire that was filled with water to increase its weight and a resistance wheel from a bike training stand to give the cyclist some resistance while pedaling. This was done to allow the cyclist to feel as if they were biking on a surface with momentum and road friction. Eight magnets along the rim of the rear wheel and a hall sensor were used to calculate the speed. A potentiometer connected to the handlebar stem measured the steering angle, and a gyroscope connected to the seat measured the roll angle. From the speed calculated from the hall sensor, the distance per frame was found to allow the cyclist to move forward. When the cyclist began to move, they were able to steer in different directions based on the steering angle from the potentiometer and the roll angle. The combination of these sensors resulted in the traversing of the cyclist through the VR world following a modified bicycle dynamics model [37][38]. A stepstool was provided for easier mounting and dismounting of the bike. Padding around the bike provided additional protection in the event a participant fell from the bike.

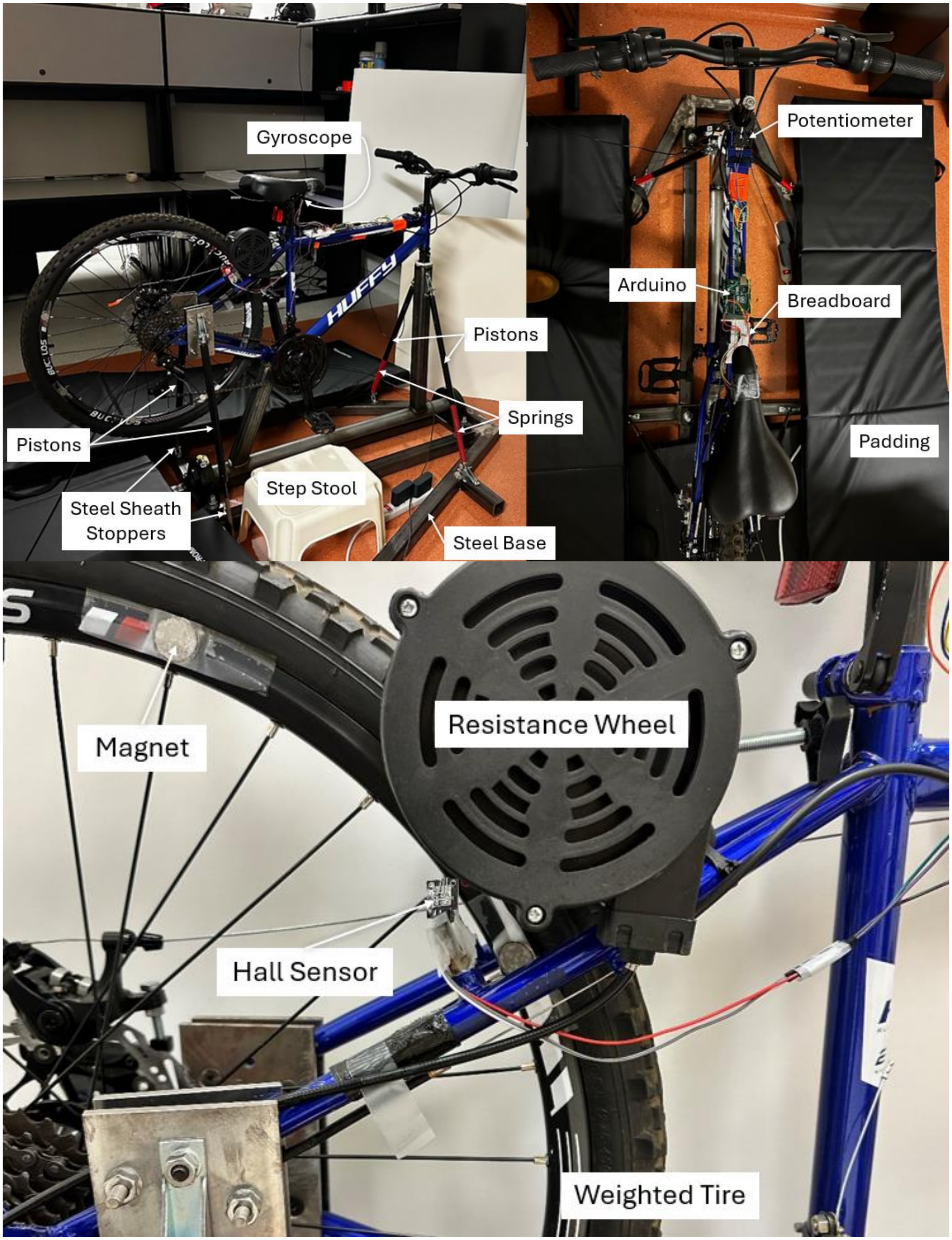


**Figure 33. Stationary bike used for the study with labeled components.**

## Study Design

A total of 18 individuals were recruited for this study based on a statistical power analysis for repeated measures ANOVA with a between-effect analysis type. For this power analysis, a power of 0.8, alpha of 0.05, effect size of 0.9, nonsphericity correction coefficient of 1, 4 groups representing the four road designs, and 3 measurements representing the three overtaking phases were used to estimate the number of participants. The participants were recruited using flyers around campus and advertisements in community newsletters (Appendix B). Individuals that showed interest in participating in the study were administered a screening questionnaire to determine if they were eligible for the study (Appendix C). Eligible participants were required to be over the age of 18 years old, have no history of epilepsy, have no medical conditions that could be aggravated by physical activity such as cycling, and have no past problems with motion/VR sickness. Once the participants were determined to be eligible, they were sent the consent form to be filled out (Appendix D). These selected participants completed a pre-test questionnaire to gauge how regularly they rode bikes and their behavior when cycling (Appendix E). Following that, participants were instructed to treat this as if they were driving on a real road and the vehicles posed a real potential danger, also to take their time if they needed to. A warning was given to inform them that leaning may cause disorientation that could lead to VR/motion sickness.

To analyze cyclist behavior during overtaking, participants experienced four scenarios: (A) the cyclist traveling in the same direction as traffic on a road with a bicycle lane but no shoulder, (B) the cyclist traveled along the flow of traffic with no bike lane and instead had a 1.5 m shoulder, (C) the cyclist traveled along the flow of traffic on a roadway that excluded both a bike lane and a shoulder, (D) the cyclist traveled along the flow of traffic on a roadway that included both a bike lane and a shoulder (Figure 32). The order of the scenarios was counterbalanced for participants in the study in order to reduce any experimental order effects. In all scenarios, the vehicles were traveling at 10 m/s or about 22 mph. The vehicles traveled in the middle of the lane when performing the overtaking and produced engine noise to give the cyclist auditory warning as they passed. Collisions were not modeled for this study. If the cyclist was in the path of the vehicle, then the vehicle just passed through and there was no collision.

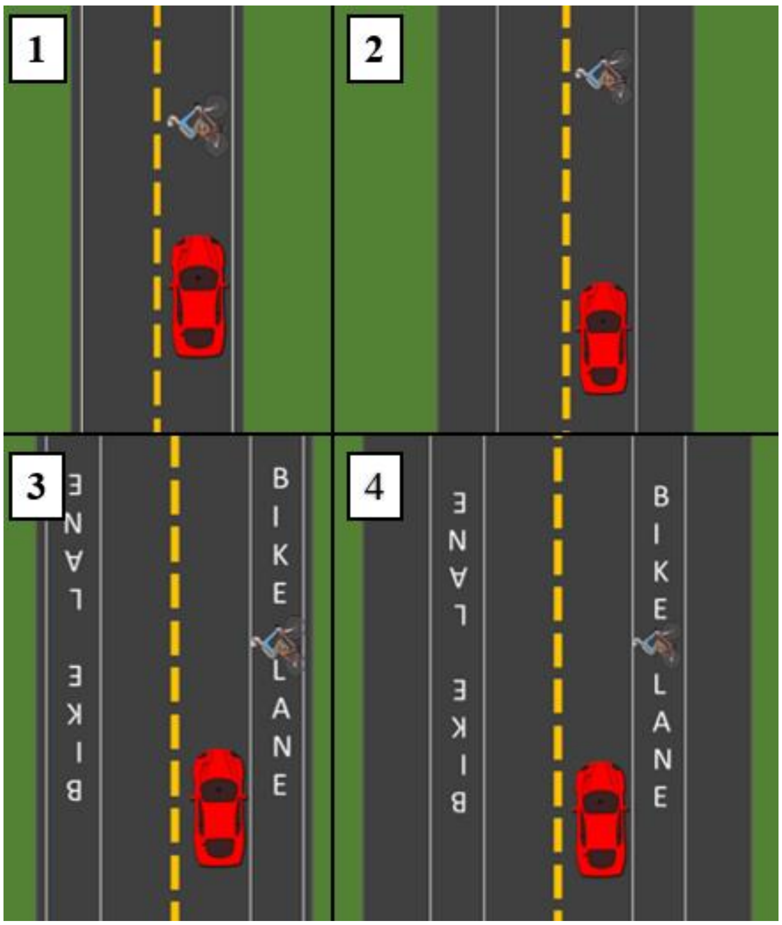



**Figure 34. Overtaking Scenarios: 1. Road with neither a shoulder nor bike lane, 2. Road with a shoulder, 3. Road with a bike lane, 4. Road with both a shoulder and bike lane.**

Following the testing, participants were asked to complete a final questionnaire (Appendix F). In the questionnaire, they rated on a scale from 0 to 10 the perceived realism and interactiveness of the VR world. The participants also rated how comfortable they were in each of the different road designs on a scale from 0 to 10. There was also a portion at the end of the questionnaire where the participants could give feedback on possible improvements to the study. This study was approved by the Internal Review Board (IRB) at Virginia Tech (IRB # 23-643).

# Chapter 4: Analysis Results

## Purpose

The purpose of this chapter is to convey the results gathered from conducting the participant testing. These results include the average speed, average lane position, standard deviation of lane position, and glance, defined as the proportion of time participants directed their gaze towards the direction of the vehicle as the vehicle performed an overtaking maneuver.

## Methods

### Data Preparation

The location and dynamics data from the bike, headset, and each vehicle were recorded separately as csv files. The dynamics data from the bike, headset, and each vehicle were joined together based on the data tables for each straight section of road where the overtaking maneuvers were recorded. Using MATLAB, the vehicle's and bike's positions were rotated and translated to have a consistent coordinate system. In this coordinate system, the vehicle's and the bike's positions were determined with respect to the edge of the road. The x-axis was perpendicular to the edge of the road and the y-axis was aligned with the road edge. Overtaking was defined as a one second window, half a second prior and half a second after the Unity given origin of bicycle and vehicle were aligned with respect to the defined y-axis. The pre-overtaking phase was defined as two seconds prior to the start of the overtaking phase. The post-overtaking phase was defined as four seconds following the end of the overtaking phase (Figure 35). This was done based on the timeline and duration of the flying overtaking scenario presented by Dozza et al. (2016) [39]. The flying overtaking scenario was defined as the vehicle traveling at a constant speed when performing the overtaking maneuver. The final analysis dataset incorporated all the pre-overtaking, post-overtaking, and overtaking data for all participants and all overtaking events. The data was structured such that the columns were defined as the dynamics, overtaking phase, order, participant number, and road type and the rows were the values with respect to the overtaking phase, order, participant number, and road type. In R, the average lane position, average speed, standard deviation of lane position (SDLP), and glance were computed for each of the different scenarios. SDLP is defined as the average distance deviated from the mean lane position, providing a measure of the variability within a lane [40]. The glance was defined as the individual turning their head 15 degrees or more to the left (i.e., towards the vehicle). Since the field of view for the headset was 110 degrees (55 degrees both directions), then if their head was turned 15 degrees, they could see up to 70 degrees to their left. The range was considered sufficient to determine if there was an attempt to look towards the vehicle.

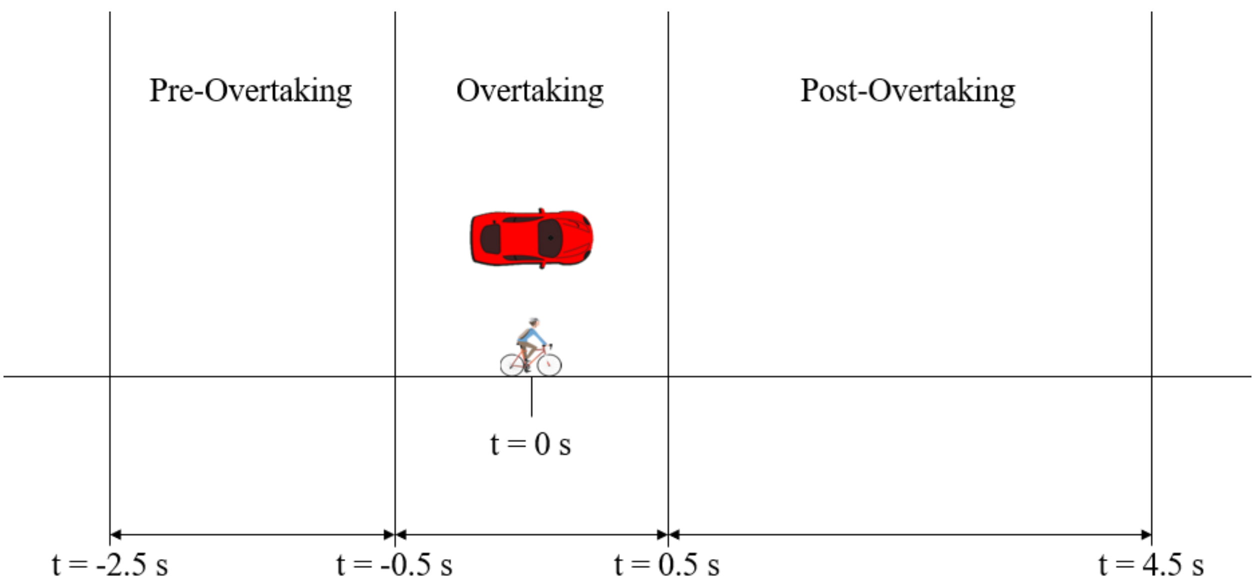



**Figure 35. Timeline of overtaking.**

### Linear Regression

A linear regression model with random effects to account for individual variation was used to determine statistical significance between speed, glance, standard deviation of lane position (SDLP), and lane position for the different road types and overtaking phases.

### Road Types

The first analysis examined differences in cyclist speed, lane position, and head and eye movement while being overtaken by a car with respect to the different road types.

### Overtaking

For the second analysis the data was stratified by the overtaking phases to determine if any differences are detectable with respect to the occurrence of overtaking.

### Comfortability

Lastly, the post-test questionnaire answers were stratified and examined for trends in the data. This analysis helped in determining other possible factors that may play a role in bicyclist behaviors during circumstances that often lead to vehicle-bicycle crashes.

## Results

The individuals that participated in this study mostly rode on sidewalks followed by roads with no bike lane and bike trails (Table 3). The least common location they rode was in a bike lane. They also mostly biked casually, and the least common usage was for transportation (Table 4).

**Table 3. Percentage of the Location the Participant Typically Biked.**

| Location | Percentage |
|---|---|
| Bike Lane | 20.5 % |
| Sidewalk | 28.2 % |
| Road with no bike lane | 23.1 % |
| Bike trail | 23.1 % |
| Other | 5.1 % |

**Table 4. Percentage of the Type of Biking the Participants Usually Participated in.**

| Type of biking | Percentage |
|---|---|
| Transportation | 21.4% |
| Casually/Leisure | 50 % |
| Exercise/Performance | 25 % |
| Other | 3.6 % |

The overall comfort and realism scores were both close to six (Table 5). indicating neither being comfortable nor being uncomfortable and neither a realistic nor unrealistic experience.

The participants in this study found it to be more comfortable when biking on roadways where there was a given space for them to bike (

Table 6). This resulted in assigning both a bike lane and a shoulder the highest comfort rating while neither was assigned the lowest comfort rating.

**Table 5. Average feel of comfort and realism for the overall VR experience.**

| Comfort & Realism | Average Score out of 10 [Standard Deviation] |
|---|---|
| Comfort | 5.9 [2.3] |
| Realism | 5.8 [1.8] |

**Table 6. Comfortability of cyclists with each road type.**

| Road Type | Average Score out of 10 [Standard Deviation] |
|---|---|
| Neither | 3.8 [1.7] |
| Shoulder | 7.1 [2.3] |
| Bike Lane | 8.1 [1.8] |
| Both | 8.5 [1.8] |

**Speed**

The speed did not change much with respect to the road type or the overtaking phase (Figure 36). The cyclist on average traveled at 4.9 m/s. The average speed was highest for the roads with a bike lane at 5.1 m/s followed by roads with a shoulder, roads with both, and roads with neither at 5 m/s, 4.8 m/s, and 4.7 m/s respectively. Based on the p-values there was no significance with respect to the overtaking phase, but there was significance between the road with neither a shoulder or a bike lane and the road with just a bike lane (Table 7). The participants tended to travel faster on the roadway with a bike lane.

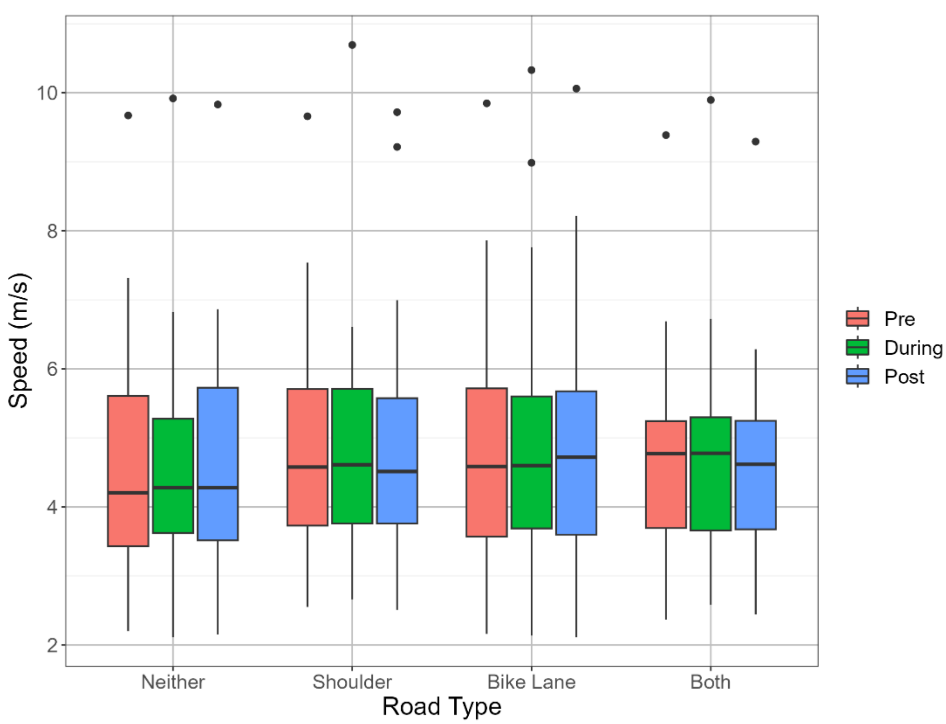


**Figure 36. Average speed with respect to road type and overtaking phase.**

**Table 7. Significance in speed difference with respect to road type and overtaking phase.**

| Covariate | | Estimate | P-Value |
|---|---|---|---|
| Road Type compared to neither bike lane nor shoulder | Shoulder | 0.187 | 0.069 |
| | Bike Lane | 0.218 | 0.039 |
| | Both | -0.092 | 0.379 |
| Overtaking phase compared to pre-overtaking | During | 0.035 | 0.691 |
| | Post | 0.041 | 0.642 |

## Glance

In the neither shoulder or bike lane scenario, the participants glanced at the overtaking vehicle for a longer percentage of the overtaking and post-overtaking phases compared to the other three road types (Figure 37, Figure 38). Based on the p-values there was significance with respect to the road type except for the road with both a shoulder and a bike lane. There was also significance between pre-overtaking and post-overtaking (Table 8).

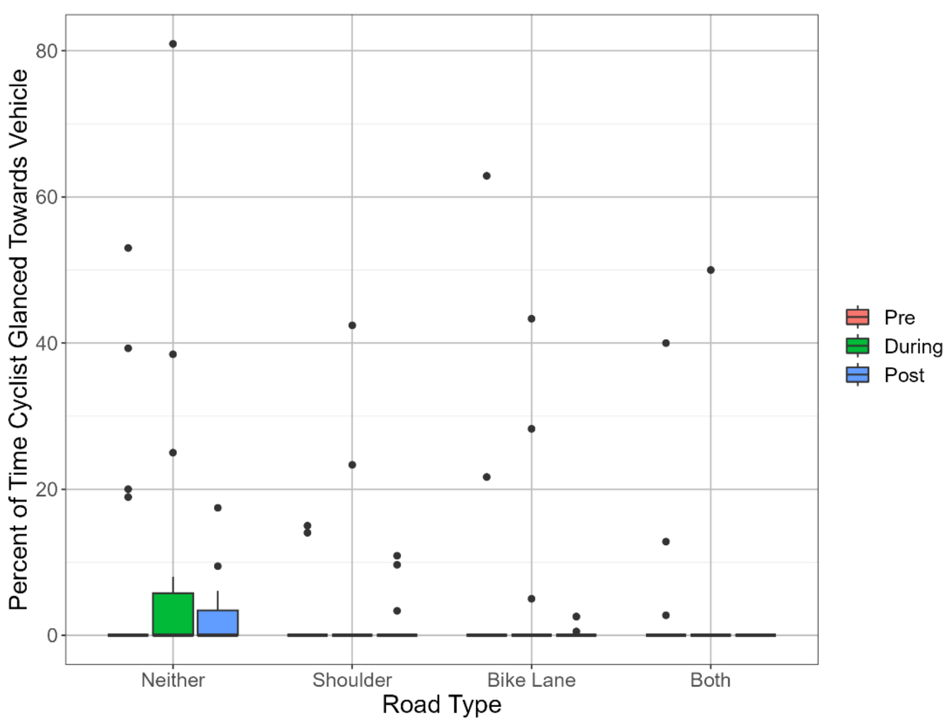


**Figure 37. The percentage of time the participant glanced towards the vehicle with respect to road type and overtaking phase.**

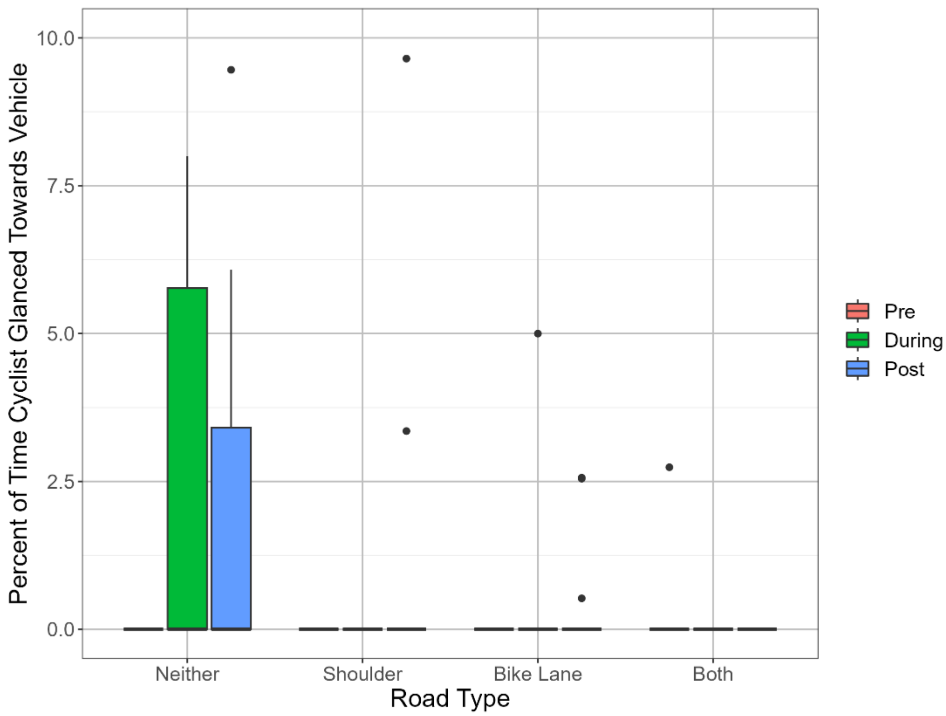



**Figure 38. Close up view of the percentage of time the participant glanced towards the vehicle with respect to road type and overtaking phase.**

**Table 8. Significance in percentage of glances with respect to road type and overtaking phase.**

| Covariate | | Estimate | P-Value |
|---|---|---|---|
| Road Type compared to neither bike lane nor shoulder | Shoulder | -4.03 | 0.04 |
| | Bike Lane | -2.555 | 0.201 |
| | Both | -3.83 | 0.056 |
| Overtaking phase compared to pre-overtaking | During | 0.778 | 0.65 |
| | Post | -3.409 | 0.048 |

## Lane Position

The participants' lane position varied depending on the road type (Figure 39). A positive lane position between 0 and 3 corresponds to the cyclist being on the roadway where the vehicle is traveling. A negative lane position corresponds to the cyclist either being off the roadway or in a designated lane for cyclists. The average lane positions for neither shoulder or bike lane, shoulder, bike lane, and both shoulder and bike lane were 0.61 m, -0.71 m, -0.48 m, and -0.69 m respectively. The p-values show that there is significance with respect to the road type (Table 9). This significance is due to the comparison being between the neither bike lane nor shoulder scenario with the other three scenarios. In the neither scenario the cyclists mostly remained on the road, while the others rode in the designated lane or on the shoulder.

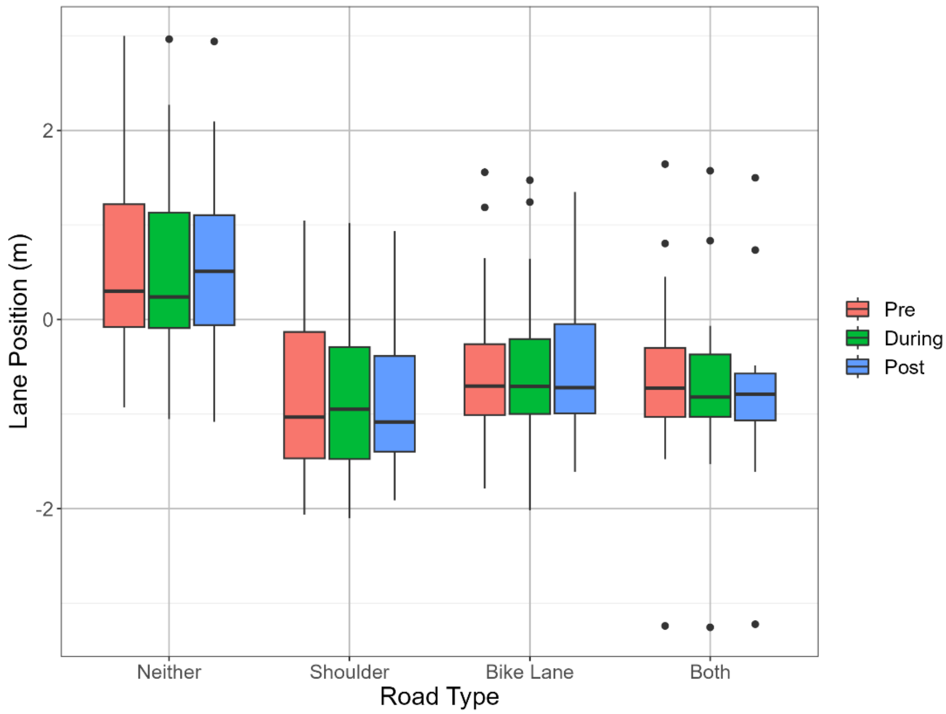



**Figure 39. Average lane position with respect to road type and overtaking phase.**

**Table 9. Significance in lane position difference with respect to road type and overtaking phase.**

| Covariate | | Estimate | P-Value |
|---|---|---|---|
| Road Type compared to neither bike lane nor shoulder | Shoulder | -1.268 | <0.001 |
| | Bike Lane | -1.013 | <0.001 |
| | Both | -1.221 | <0.001 |
| Overtaking phase compared to pre-overtaking | During | -0.047 | 0.765 |
| | Post | -0.042 | 0.79 |

**SDLP**

The standard deviation of lane position did not vary significantly with respect to the road type or to the overtaking phase (Figure 40). The neither shoulder or bike lane scenario had the highest average SDLP at 0.55 m followed by shoulder, bike lane, then both at 0.45 m, 0.41 m, and 0.37 m respectively. In the neither shoulder or bike lane scenario, the SDLP has a larger interquartile range (IQR) and the both shoulder and bike lane scenario has the smallest IQRs. The higher IQR means there is a lower predictability of the cyclist's movements. This is due to high IQR representing larger statistical dispersion and more variability [41]. The roads without a designated spot for cyclists to ride caused the cyclists to act in a less predictable manner. Based on the p-values, however, there was no significance with respect to the road type or the overtaking phase (Table 10).

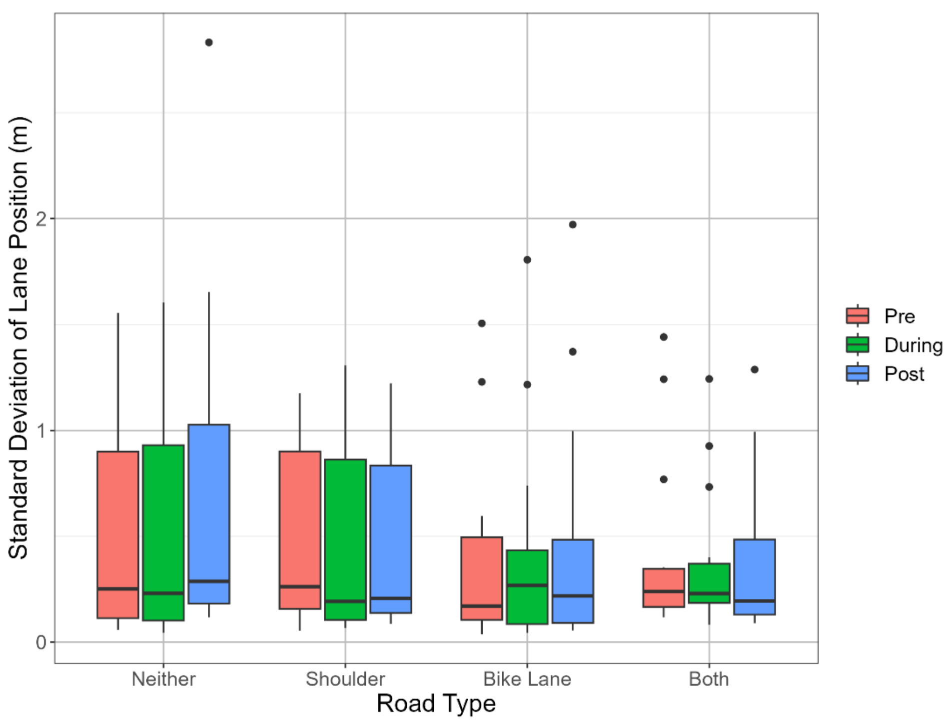


**Figure 40. SDLP with respect to road type and overtaking phase.**

**Table 10. Significance in SDLP difference with respect to road type and overtaking phase.**

| Covariate | | Estimate | P-Value |
|---|---|---|---|
| Road Type compared to neither bike lane nor shoulder | Shoulder | -0.102 | 0.258 |
| | Bike Lane | -0.136 | 0.139 |
| | Both | -0.172 | 0.061 |
| Overtaking phase compared to pre-overtaking | During | -0.006 | 0.935 |
| | Post | 0.0531 | 0.505 |

## Discussion

The speed for each road type and overtaking phase did not vary significantly. The average speed was 4.9 m/s with outliers as high as 10.7 m/s. The average speeds when overtaking is occurring and not occurring were all within 0.03 m/s of the average. The participants were told to bike as if they were in real-life and there was no specific speed they were told to travel at. They naturally traveled at a speed similar to those used in Euro NCAP tests. In the Euro NCAP, the bicyclist travels either 15 or 20 km/h, while in the current testing scenarios the participants average speed was 17.6 km/h. The current scenarios, however, were not fully representative of fatal crash speed. A total of 56% of the crashes occurred when the speed limit on the road was either 35, 45, or 55 mph. In contrast, the vehicle performing the overtaking traveled 10 m/s or about 22.4 mph. Future work could examine the effects of higher vehicle speeds.

Compared to the road with neither a shoulder or a bike lane, there was a significant difference in the proportion of time the cyclists glanced towards the overtaking vehicle on the roadway with just a shoulder. In the case where there was neither a bike lane or a shoulder, the cyclists looked towards the vehicle more than for other scenarios. This could be correlated to the participants' comfortability during the scanario. When cyclists are not given lateral separation from the vehicle through a bike lane or shoulder, they may be looking to see if the vehicle is going to provide them with that lateral separation. As for the lane position, in the scenario where the cyclist has neither a shoulder or a bike lane, the cyclists travel more in the travel lane than in the other three scenarios. When given both a shoulder and a bike lane, however, some cyclists still traveled on the road instead of using the bike lane or shoulder.

The neither shoulder or bike lane scenario has the largest IQR and average standard deviation of lane position. The both shoulder and bike lane scenario has the smallest IQR. A larger IQR means there is a lower predictability of the cyclist's movements when they are riding on a roadway with no support lane. This is important for systems like forward collision warning (FCW) and automatic emergency braking (AEB). When these systems detect a bicyclist with a predictable amount of SDLP, the system can be prepared to engage to mitigate a possible crash with the bicyclist. In the neither shoulder nor bike lane cases, the participants' SDLP was an average of 0.54 meters and was as high as 2.5 meters. ADAS needs to take into account the worst cases to prevent as many crashes as possible.

The individuals recruited for this study were all college students, resulting in participants average age being 22.7 years old, with a minimum age of 20 years old, a maximum of 29 years old, and a median of 22 years old. This demographic contrasts with the age of cyclists involved in fatal crashes between 2014 and 2020, with the average being 56.1 years old with a median of 50 years old. Age could play a major role in the likelihood of a crash. Since the average age cyclists involved in fatal crashes are much higher than those in this study, there may be some difference in results due to the older individuals possible having a slower reaction time, lower ability to hear and see, and lower mobility. But there is a possibility that the fatally injured cyclist data may be skewed due to the older individuals possibly having a higher probability of dying from a crash compared to younger individuals.

A post-test questionnaire was given to the participants where they answered how they perceive their behavior as a cyclist, how did they feel about the different road infrastructures, how they usually perform an overtaking maneuver as a driver, and did their experience change their view of overtaking. The result was that they perceived that they behaved in a manner similar to what they would have in the real world. Most of the participants mention that having some allocated space whether that was a bike lane or shoulder, or both, they felt more comfortable. Having neither made them uncomfortable and invoked a feeling of danger. As for how they usually overtake as a driver, they mentioned that they usually give as much space as they possibly can to cyclists, especially if there is no designated lane for them. There were a mix of answers in terms of if the experience changed their view of overtaking. Most mentioned that it did change their perspective, giving them a better understanding of the cyclist's point of view of how close the vehicles can feel when an overtaking maneuver is performed and how uncomfortable it can be as a cyclist. Other participants mentioned that it did not really change their perspective.

The results collectively show the participants had a much different reaction to roadways that provided lateral space compared to those that did not. They were much more comfortable, had a lower SDLP, glanced towards the overtaking vehicle less, and traveled faster when given designated space to travel (Table 11). Therefore, it appears that cyclists need this designated space to feel more comfortable, ride with more predictability, and improve roadway safety. A couple of ways this designated space could be implemented include the addition of bike lanes, bike trails that travel parallel to the roadway, and wider travel lanes. It can also be stated that companies that implement ADAS in vehicles need to understand the cyclists' behavior difference when designing systems meant to prevent bicycle crashes. One of the most significant factors that needs to be taken into account is the SDLP of cyclists, especially when travelling on a roadway with neither a bike lane nor a shoulder. Understanding how much the SDLP values can vary would be important for the effective testing to improve these systems.

**Table 11. Summary of Results**

| Road Type | Speed | Glance | Lane Position | Standard Deviation of Lane Position | Comfort |
|---|---|---|---|---|---|
| Neither Bike Lane or Shoulder | Lowest | Most | On Road | Highest | 3.8/10 |
| Shoulder | - | - | On Shoulder | - | 7.1/10 |
| Bike Lane | Highest | - | In Bike Lane | - | 8.1/10 |
| Both Bike Lane and Shoulder | - | - | In Bike Lane | Lowest | 8.5/10 |

## Limitations

The first and one of the most important limitations was how realistic the bicycle felt to each of the participants. The participants were informed before the start of the study to treat this as if they were in the real-life scenarios and the vehicles that performed the overtaking posed a real potential danger. They were also informed that there are aspects and dynamics of the bicycle make-up that would not feel like the real thing. One of these aspects was the resistance while pedaling, which was not exactly like a real bike. Also, there was little to no coasting when the cyclist stopped pedaling. That could play a role in the cyclist fatiguing faster than on an actual bike. Another limitation was the ability to lean and turn by bicycle roll, which caused disorientation for some participants. Finally, when riding a bike there is usually some wind/air resistance that the cyclist feels. That aspect was not incorporated into the design of the stationary bike.

When considering the environment itself, there were also some limitations that should be improved upon by future research. For example, when the cyclist was on the bike they could not see where their hands and body were, which caused some initial confusion. The roads were also straight and flat which is not realistic in most cases. Instead, there are usually curves and hills on roadways that could play a role in the cyclist's comfortability. Another environmental limitation that was mentioned by participants was the lack of road texture felt mainly on the shoulder section of the road. One cyclist mentioned that the shoulder is usually rougher and has some debris. In addition, the vehicles that overtook the cyclist in VR were only of one type: 2-door passenger vehicle. There are, however, multiple types of vehicles that perform overtaking on cyclists. In fact, one of the participants mentioned that trucks made them much more uncomfortable when they tried to perform overtaking. Finally, another limitation was that the cars that were overtaking in the VR were not adaptive to the cyclists. They remained in the middle of the lane they were traveling in. Usually when a vehicle is overtaking, they will try to move away from the cyclist and afford them some additional space.

# Chapter 5: Conclusions and Future Work

## Implications

This research aimed to provide insight into bicyclist behavior in the most fatal real-world scenarios involving vehicles and cyclists. Most existing research on vehicle-bicycle interactions, primarily focused on motorists, has been conducted outside the United States and often involved naturalistic studies. In terms of contributing to existing knowledge, the study reveals that a majority of fatal bicycle crashes occur when a vehicle performs an overtaking maneuver, with cyclists traveling in traffic lanes, and not within intersections. Despite the underreporting of crashes involving cyclists, this study was developed using known information from FARS and associated literature. Participants were recruited to bike in a virtual reality simulation where vehicles performed overtaking maneuvers on four different road types. This was done to provide insight into cyclist behavior without exposing them to real-world dangers. The results suggest that cyclists prefer roadways with designated lanes or at least extra space for vehicles to pass safely. Participants rated roadways with both bike lanes and shoulders the highest, while those lacking designated spaces received lower ratings. Moreover, their position within the road varied more without a designated space to bike, increasing unpredictability for drivers attempting overtaking maneuvers and for advanced driver assistance systems (ADAS) like automatic emergency braking (AEB).

## VR Simulator Improvements

This study could be improved in the future by improving the graphics of the environment. There should be an addition of other roads, more buildings, sidewalks, and other road users. There could also be the implementation of pedestrians and traffic lights. These additional objects and road users could provide the cyclist with a more realistic and immersive environment.

The bike could also include some coasting dynamics. There was little to no coasting for the current version of the study but including it would make the environment more realistic and less taxing on the cyclist. There also could be the implementation of adaptive vehicles that give the cyclist space when performing the overtaking, as well as a way the cyclist can lean and still be stable to prevent disorientation and the feeling of falling.

Participants mentioned that there should be an implementation of different vehicle types, like SUVs, small pickup trucks, and tractor trailers. This would make the environment more realistic and allow for a better analysis of the comfort of the road types and a comparison of comfort across different vehicles. Observing the comfort level of the different vehicle types could possibly be used to implement different spacing regulations for the different vehicle types. It was also mentioned by participants that there should be different types of bike lanes. One commented that there should be a bike lane with a space between it and the road. Another suggestion was a bike lane with a divider, whether that was a raised median, or barriers. Then there was the consideration of adding different textures to the road. For example, when riding on a shoulder or road with neither a shoulder nor bike lane, there is usually debris that causes cyclists to ride further in the vehicle travel lane.

## Future Implications

For future work that includes bicyclists and their safety, how bicyclists interact in different situations should be observed. The main focus of these observations should be on age, the direction and the location the cyclists are traveling, and how they interact with vehicles. Some other things that need to be considered are helmet use, time of day, and blood alcohol concentration. Helmet use results in less fatalities in crashes [33]. In a future study, the cyclist roadway interaction with respect to helmet use could be observed to see if cyclist riding aggression changes. Also, the time of day that a majority of the crashes happened was at night between 6 and midnight [33]. A study can be run in different lighting to take time of day into account. They also happen mostly between June and August, which is usually when the weather is warmer, and more individuals may ride for leisure purposes. As for the BAC, about 25% of all bike crashes are cause by the cyclist being classified as legally drunk with a BAC of 0.08% of higher [33]. Observing how cyclists behave differently when having a BAC of at least 0.08% versus being sober could be another factor to consider.

## Conclusions

To further promote the development and installation of bicycle-detecting AEB systems in the US, the US NCAP or IIHS may consider bicycle-detecting AEB testing. Based on this study, the US-specific scenarios would be a vehicle traveling between 10 m/s and 20 m/s with a bicycle traveling in the same direction as the vehicle at 5 m/s. The bicycle should start at varied locations starting from about a 0.5 meter offset to the right of the vehicle up to 50% of the width of the vehicle. This is similar to Euro NCAP's VRU testing protocol, which many systems can pass already. There could also be implementations of lateral movement within the range suggested by this study. Such testing could lead to improvements in AEB systems, reducing injury severity and increasing cyclist predictability, particularly on roadways lacking designated cycling lanes. Suggestions for road infrastructure improvements include increasing the number of bike lanes, adding wider shoulders, or even widening lanes to enhance cyclist safety on roadways.

In conclusion, this study found that cyclists should have a dedicated space for them to ride, whether that is a bike lane (with or without a separator), a bike trail parallel to the roadway, or a wider travel lane. Cyclists were more comfortable and had less lateral movement when they were given that space. To mitigate crashes when cyclists are not given the space they need to ride comfortably, bicycle-detecting AEB needs to be implemented in vehicles. The companies developing and testing these bicycle-detecting AEB systems need to take the range of possible bicyclists SDLP into account. This is especially the case for roadways with no designated space for cyclists considering they had the highest SDLP in those cases. This will allow the system to predict the bicyclists' movement better and increase overall system effectiveness.

# References

[1] "Fatality Facts 2021: Bicyclists," IIHS-HLDI crash testing and highway safety. Accessed: Jul. 11, 2023. [Online]. Available: https://www.iihs.org/topics/fatality-statistics/detail/bicyclists

[2] "National Efforts | FHWA." Accessed: Apr. 02, 2024. [Online]. Available: https://highways.dot.gov/safety/zero-deaths/national-efforts

[3] NHTSA, "Bicyclists and other cyclists: 2020 data (Traffic Safety Facts. Report No. DOT HS 813 322)," Traffic Safety Facts 2020 Data. Accessed: Mar. 25, 2024. [Online]. Available: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813322

[4] "Fatality Facts 2021: Yearly snapshot," IIHS-HLDI crash testing and highway safety. Accessed: Apr. 02, 2024. [Online]. Available: https://www.iihs.org/topics/fatality-statistics/detail/yearly-snapshot

[5] R. Fredriksson, K. Fredriksson, and J. Strandroth, *Pre-crash motion and conditions of bicyclist-to-car crashes in Sweden*. 2014. doi: 10.13140/2.1.1454.0481.

[6] "Sustainability | Free Full-Text | The Analysis of the Factors Influencing the Severity of Bicyclist Injury in Bicyclist-Vehicle Crashes." Accessed: Mar. 21, 2023. [Online]. Available: https://www.mdpi.com/2071-1050/14/1/215

[7] A. V. Olesen, T. K. O. Madsen, T. Hels, M. Hosseinpour, and H. S. Lahrmann, "Single-bicycle crashes: An in-depth analysis of self-reported crashes and estimation of attributable hospital cost," *Accid. Anal. Prev.*, vol. 161, p. 106353, Oct. 2021, doi: 10.1016/j.aap.2021.106353.

[8] K. Gildea, D. Hall, and C. Simms, "Configurations of underreported cyclist-motorised vehicle and single cyclist collisions: Analysis of a self-reported survey," *Accid. Anal. Prev.*, vol. 159, p. 106264, Sep. 2021, doi: 10.1016/j.aap.2021.106264.

[9] D. Shinar *et al.*, "Under-reporting bicycle accidents to police in the COST TU1101 international survey: Cross-country comparisons and associated factors," *Accid. Anal. Prev.*, vol. 110, pp. 177–186, Jan. 2018, doi: 10.1016/j.aap.2017.09.018.

[10] A. Rasch, C.-N. Boda, P. Thalya, T. Aderum, A. Knauss, and M. Dozza, "How do oncoming traffic and cyclist lane position influence cyclist overtaking by drivers?" *Accid. Anal. Prev.*, vol. 142, p. 105569, Jul. 2020, doi: 10.1016/j.aap.2020.105569.

[11] C. Llorca, A. Angel-Domenech, F. Agustin-Gomez, and A. Garcia, "Motor vehicles overtaking cyclists on two-lane rural roads: Analysis on speed and lateral clearance," *Saf. Sci.*, vol. 92, pp. 302–310, Feb. 2017, doi: 10.1016/j.ssci.2015.11.005.

[12] I. Walker, "Drivers overtaking bicyclists: Objective data on the effects of riding position, helmet use, vehicle type and apparent gender," *Accid. Anal. Prev.*, vol. 39, no. 2, pp. 417–425, Mar. 2007, doi: 10.1016/j.aap.2006.08.010.

[13] M. D. Vu *et al.*, "An Analysis of Vulnerable Road Users Overtaking Maneuver along the Urban Road," *Appl. Sci.*, vol. 11, no. 14, Art. no. 14, Jan. 2021, doi: 10.3390/app11146361.

[14] O. Lee, A. Rasch, A. L. Schwab, and M. Dozza, "Modelling cyclists' comfort zones from obstacle avoidance manoeuvres," *Accid. Anal. Prev.*, vol. 144, p. 105609, Sep. 2020, doi: 10.1016/j.aap.2020.105609.

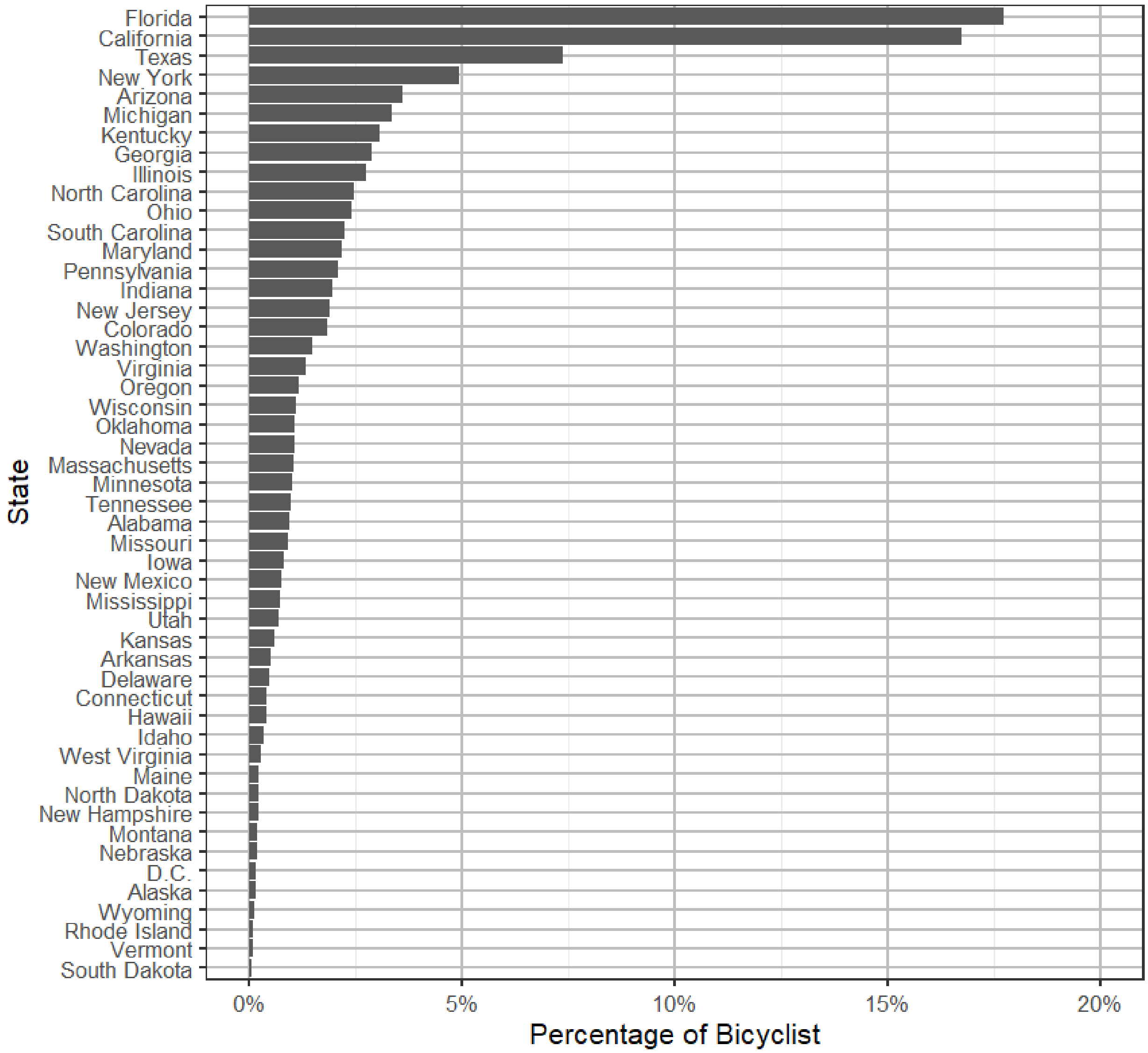
[15] H. Farah, G. Bianchi Piccinini, M. Itoh, and M. Dozza, "Modelling overtaking strategy and lateral distance in car-to-cyclist overtaking on rural roads: A driving simulator experiment," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 63, pp. 226–239, May 2019, doi: 10.1016/j.trf.2019.04.026.

[16] A. Rasch, S. Moll, G. López, A. García, and M. Dozza, “Drivers’ and cyclists’ safety perceptions in overtaking maneuvers,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 84, pp. 165–176, Jan. 2022, doi: 10.1016/j.trf.2021.11.014.
[17] C. Liu, R. Fujishiro, L. Christopher, and J. Zheng, “Vehicle–Bicyclist Dynamic Position Extracted from Naturalistic Driving Videos,” *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 4, pp. 734–742, Apr. 2017, doi: 10.1109/TITS.2016.2586104.
[18] D. P. Cobb, H. Jashami, and D. S. Hurwitz, “Bicyclists’ behavioral and physiological responses to varying roadway conditions and bicycle infrastructure,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 80, pp. 172–188, Jul. 2021, doi: 10.1016/j.trf.2021.04.004.
[19] L. Thomas, K. Nordback, and R. Sanders, “Bicyclist Crash Types on National, State, and Local Levels: A New Look,” *Transp. Res. Rec.*, vol. 2673, no. 6, pp. 664–676, Jun. 2019, doi: 10.1177/0361198119849056.
[20] “Virtual Reality Driving Simulator Based on Head-Mounted Displays | SpringerLink.” Accessed: Mar. 21, 2023. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-319-49448-7_15
[21] E. Chang, H. T. Kim, and B. Yoo, “Virtual Reality Sickness: A Review of Causes and Measurements,” *Int. J. Human–Computer Interact.*, vol. 36, no. 17, pp. 1658–1682, Oct. 2020, doi: 10.1080/10447318.2020.1778351.
[22] S. M. Taheri, K. Matsushita, and M. Sasaki, “Virtual Reality Driving Simulation for Measuring Driver Behavior and Characteristics,” *J. Transp. Technol.*, vol. 07, no. 02, Art. no. 02, 2017, doi: 10.4236/jtts.2017.72009.
[23] G. Matthews, L. Dorn, T. W. Hoyes, D. R. Davies, A. I. Glendon, and R. G. Taylor, “Driver Stress and Performance on a Driving Simulator,” *Hum. Factors*, vol. 40, no. 1, pp. 136–149, Mar. 1998, doi: 10.1518/001872098779480569.
[24] “Assessing the impact of three intersection treatments on bicyclist safety using a bicycling simulator - ScienceDirect.” Accessed: Mar. 21, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0001457522003128?dgcid=rss_sd_all
[25] T. Murano, T. Yonekawa, M. Aga, and S. Nagiri, “Development of High-Performance Driving Simulator,” *SAE Int. J. Passeng. Cars - Mech. Syst.*, vol. 2, no. 1, Art. no. 2009-01–0450, Apr. 2009, doi: 10.4271/2009-01-0450.
[26] “Potential Effectiveness of Bicycle-Automatic Emergency Braking using the Washtenaw Area Transportation Study Data Set - Samantha H. Haus, Ryan M. Anderson, Rini Sherony, Hampton C. Gabler, 2021.” Accessed: Sep. 29, 2023. [Online]. Available: https://journals.sagepub.com/doi/abs/10.1177/03611981211001377?casa_token=X801_DvxEGQAAAAA%3A4RbRKgWC2M4Wg0GvLPOR1HCYnks_iKU5Q42WUvnK5apfX3NVszS8tBdkolV9XchZXvnmsQJX3TcEA24&journalCode=trra
[27] A. Kullgren, K. Amin, and C. Tingvall, “Effects on crash risk of automatic emergency braking systems for pedestrians and bicyclists,” *Traffic Inj. Prev.*, vol. 24, no. sup1, pp. S111–S115, Apr. 2023, doi: 10.1080/15389588.2022.2131403.
[28] *Safety Companion Knowledge for Tomorrow’s Automotive Engineering 2024*, 1.5. carshs.training gmbh.
[29] “U.S. Americans who went bicycling 2021,” Statista. Accessed: Mar. 31, 2023. [Online]. Available: https://www.statista.com/statistics/191204/participants-in-bicycling-in-the-us-since-2006/

[30] A. Marcotte, “Today in Gender Gaps: Biking,” *Slate*, Sep. 17, 2014. Accessed: Mar. 31, 2023. [Online]. Available: https://slate.com/human-interest/2014/09/gender-gap-alert-men-ride-bikes-way-more-than-women-do.html
[31] “AEB Cyclist | Euro NCAP.” Accessed: Apr. 08, 2024. [Online]. Available: https://www.euroncap.com:443/en/car-safety/the-ratings-explained/vulnerable-road-user-vru-protection/aeb-cyclist/
[32] “Fatality Facts 2020: Bicyclists,” IIHS-HLDI crash testing and highway safety. Accessed: Mar. 31, 2023. [Online]. Available: https://www.iihs.org/topics/fatality-statistics/detail/bicyclists
[33] “Fatality Facts 2020: Bicyclists,” IIHS-HLDI crash testing and highway safety. Accessed: Apr. 11, 2023. [Online]. Available: https://www.iihs.org/topics/fatality-statistics/detail/bicyclists
[34] “Pedestrians and bicyclists: Bicycle helmet use laws,” IIHS-HLDI crash testing and highway safety. Accessed: May 10, 2024. [Online]. Available: https://www.iihs.org/topics/pedestrians-and-bicyclists/bicycle-helmet-use-laws-table
[35] “Mitigation Strategies for Design Exceptions - Safety | Federal Highway Administration.” Accessed: Apr. 08, 2024. [Online]. Available: https://safety.fhwa.dot.gov/geometric/pubs/mitigationstrategies/chapter3/3_lanewidth.cfm
[36] “swless19.pdf.” Accessed: Apr. 08, 2024. [Online]. Available: https://safety.fhwa.dot.gov/PED_BIKE/univcourse/pdf/swless19.pdf
[37] K. J. Astrom, R. E. Klein, and A. Lennartsson, “Bicycle dynamics and control: adapted bicycles for education and research,” *IEEE Control Syst. Mag.*, vol. 25, no. 4, pp. 26–47, Aug. 2005, doi: 10.1109/MCS.2005.1499389.
[38] “Bicycle vehicle model - MATLAB.” Accessed: Apr. 14, 2024. [Online]. Available: https://www.mathworks.com/help/robotics/ref/bicyclekinematics.html
[39] M. Dozza, R. Schindler, G. Bianchi-Piccinini, and J. Karlsson, “How do drivers overtake cyclists?” *Accid. Anal. Prev.*, vol. 88, pp. 29–36, Mar. 2016, doi: 10.1016/j.aap.2015.12.008.
[40] J. Verster and T. Roth, “Standard Operation Procedures for conducting the on-the-road driving test, and measurement of the standard deviation of lateral position (SDLP),” *Int. J. Gen. Med.*, vol. 4, pp. 359–71, May 2011, doi: 10.2147/IJGM.S19639.
[41] “Explore your Data: Range, interquartile range and box plot,” MAKE ME ANALYST. Accessed: Apr. 14, 2024. [Online]. Available: https://makemeanalyst.com/explore-your-data-range-interquartile-range-and-box-plot/

# Appendix

## Appendix A



## Appendix B

# Participants Needed for Research Study

COLLEGE OF ENGINEERING
CENTER FOR INJURY BIOMECHANICS
VIRGINIA TECH

The SAFETY IMPACT Lab is recruiting individuals for a 60-minute single visit study (IRB # 23-643).

The purpose of this study is to use virtual reality (VR) to characterize bicyclist behavior as they share the road with vehicles. Eligible participants will complete two online surveys, one administered before and one after testing. Each survey should take no longer than 10 minutes to complete. Testing should take no longer than 20 minutes to complete for a total duration of less than 1 hour.

### Eligibility Requirements:

- Age: 18+
- Experience biking on roadways
- No history of epilepsy
- No history of VR/motion sickness
- No medical condition that might be aggravated due to exercise.

Below is a QR code you can use to complete the screening questions if you would like to participate in the study.

FOR MORE INFORMATION: contact Eugene Crump at cray2@vt.edu

# Appendix C

## *VR Bike Screening Questionnaire*

**Introductory Statement:**

(Screener's script for the screening interview)

*"Hello. My name is _____ and I'm with the SAFETY IMPACT Lab at Virginia Tech, in Blacksburg, VA. We are currently recruiting eligible individuals to participate in a research study assessing bicyclist behavior as they interact with vehicles to improve the crash avoidance of ADAS. Specifically, participants will be asked to sit on a stationary bike and bike around a virtual reality (VR) environment. This study would involve coming to our facility for a single 1 hour session. An experimenter will be with you at all times."*

*"Since you have indicated interest in possibly participating, I need to go over some screening questions to see if you meet all the eligibility requirements of this study. Any information given to us will be kept secure and confidential."*

***If you no longer wish to be considered for the study, please let us know and do not provide us with any additional personal information. If yes, please download and fill out the form below as soon as possible. <u>By returning the completed form, you are consenting to provide the research team with the screening information below.</u>***

**cray2@vt.edu** Switch account

* Indicates required question

Email *

Your email

What is your current age? *

Your answer

Are you willing to show identification at the time of participation in order to verify your age? *

- ○ Yes
- ○ No

What is your sex?

- ○ Male
- ○ Female
- ○ Prefer not to answer

Are you available to come in for a 1-hour session, during standard business hours (M-F, 8-5)? *

- ◯ Yes
- ◯ No

You will be asked to ride on a stationary bike for around 20 minutes. Would this present a problem for you? *

- ◯ Yes
- ◯ No

Do you have any medical conditions that might be aggravated due to exercise or using the bicycle? *

- ◯ Yes
- ◯ No

Have you had any previous problems with motion sickness/VR sickness? *

- ◯ Yes
- ◯ No

If you answered yes to the previous question, please explain. *

Your answer

Do you have epilepsy? *

- ○ Yes
- ○ No

Do you currently wear corrective lenses? (if you wear contacts mark NO) *

- ○ Yes
- ○ No

How did you hear about this project?

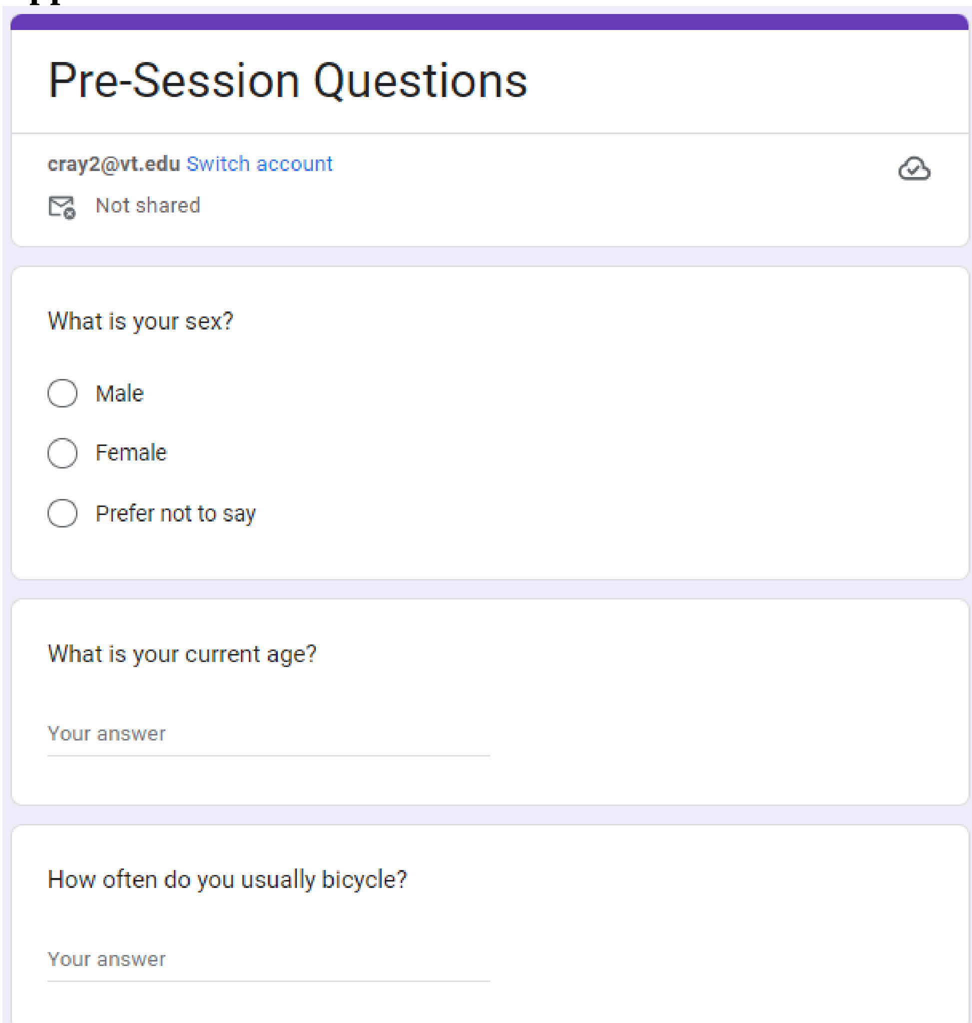
Your answer

Submit

Clear form

# Appendix D

## Appendix E



# Pre-Session Questions

cray2@vt.edu Switch account

Not shared

What is your sex?

- ◯ Male
- ◯ Female
- ◯ Prefer not to say

What is your current age?

Your answer

How often do you usually bicycle?

Your answer

What best describes your usual biking? (Can choose multiple)

- [ ] Transportation (ex. to work/school)
- [ ] Casually/Leisure
- [ ] Exercise/performance (ex. mountain biking or racing)
- [ ] Other

If you marked other in the previous question, describe how you usually bike.

Your answer

Which location do you bike? (Can choose multiple)

- [ ] Bike Lane
- [ ] Sidewalk
- [ ] Roads with no bike lane
- [ ] Bike Trail
- [ ] Other

If you marked other in the previous question, describe where you usually bike.

Your answer

Have you ever been in a crash with a vehicle while riding a bicycle? If so, please describe how the crash happened?

Your answer

Are you near-sighted or far-sighted?

- ◯ Near-sighted
- ◯ Far-sighted
- ◯ Neither

Do you have any questions before we continue?

Your answer

Submit

Clear form

# Appendix F

## Post-Test Questions

cray2@vt.edu Switch account

Not shared

**Rate your total comfort from 1-10 (where 1 is very uncomfortable, 5 is neither comfortable nor uncomfortable, and 10 is very comfortable)**

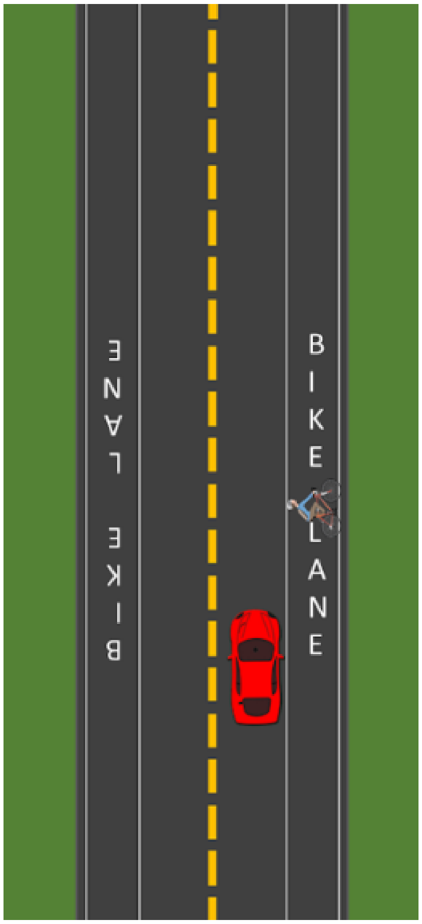
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Very Uncomfortable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very Comfortable |

**Rate how realistic the environment felt from 1-10 (1 is very unrealistic and 10 is very realistic)**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Very Unrealistic | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very Realistic |

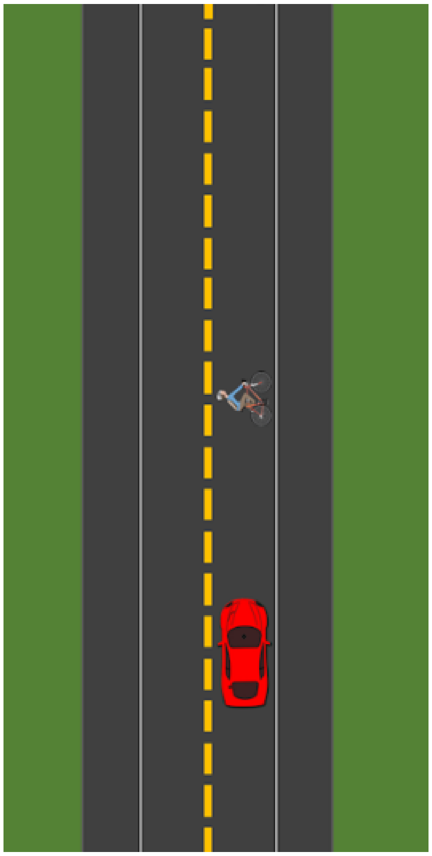
**Rate of your comfort from 1-10 for each of the following scenarios that you experienced (using the same scale from question 1)**

Road with a bike lane



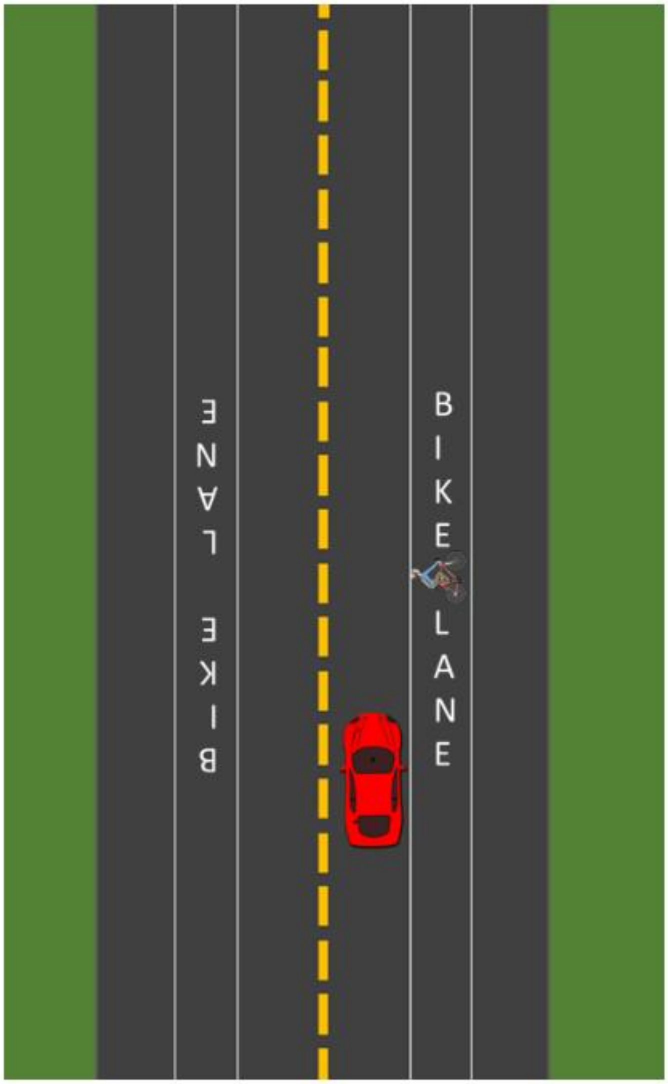

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Very Uncomfortable | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very Comfortable |

Road with a shoulder



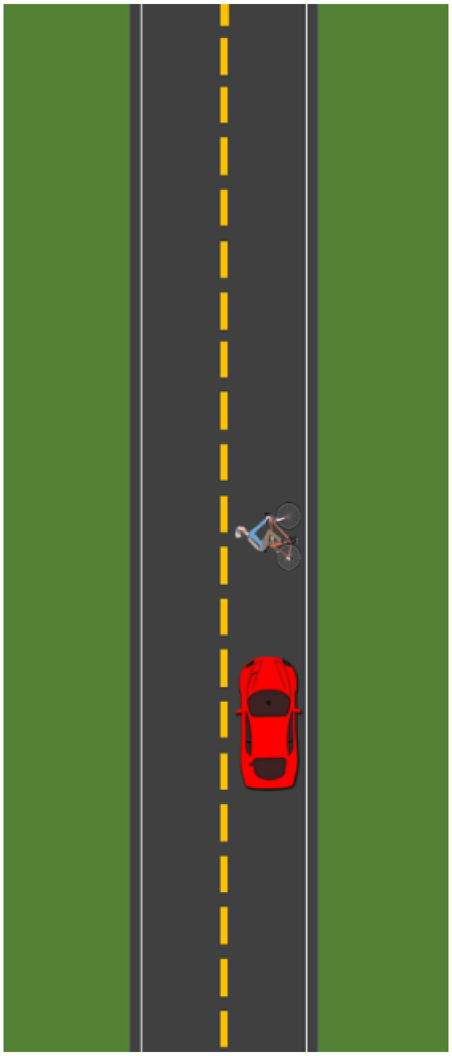
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Very Uncomfortable | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very Comfortable |

Road with both a bike lane and a shoulder




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Very Uncomfortable | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very Comfortable |

Road with neither a bike lane or a shoulder



| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Very Uncomfortable | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very Comfortable |

**How do you think you behaved as a cyclist? For example, do you think you behaved the same way you would have in a real-world situation?**

Your answer

**Describe how you usually overtake bicyclists when you are driving a vehicle.**

Your answer

**Did this experience change how you view this kind of overtaking? If it did, how?**

Your answer

**How do you feel about the different infrastructures? Is there anyone that you would prefer to drive on over the others? (Using the pictures from question 3)**

Your answer

**Any other thoughts that you would like to share with us?**

Your answer

Submit

Clear form