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Real Time Bicycle Simulation Study of Bicyclists' Behaviors and their Implication on Safety

FINAL REPORT

Valerian Kwigizile, Jun-Seok Oh, Pavel Ikonomov, Raed Hasan, Cole G. Villalobos, Aous Hammad Kurdi, and Anil Shaw

Transportation Research Center for Livable Communities
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The main goal of this study was to build a bicycle simulator and study the interaction between cyclists and other roadway users. The simulator developed was used in conjunction with Oculus Rift googles to create a virtual cycling environment. The virtual riding environment contained roadway infrastructures and features such as intersections, crosswalks, bicycle lanes, shared-lanes, etc. It also contained both motor vehicles and pedestrians that interacted with cyclists. The rider's perception and reactions to different situations were investigated based on their performance during four virtual simulation scenarios with an electroencephalogram (EEG) readings. In addition to the results on interactions of cyclists and other roadway users and the infrastructure obtained from this study, the simulator developed can be used for future studies.</td></tr>
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1 Introduction and Background

1.1 Background and Motivation

There are many countries in Europe and Asia where a bicycle is the main mode of transportation. In these countries, road infrastructure has been built to accommodate bicyclist as an equal partner on the road or path and to share space with motorized vehicles and pedestrians. However, in North America, many roads are built for motorized vehicles with little accommodation of pedestrians and bicycles. Also, pedestrian paths and alleys are built exclusively for walking. Recently, the big growth of bicycles on the roads in North America has created safety issues for a bicyclist on the road as they move relatively slower than motorized vehicles, rendering them prone to collision with motor vehicle (Goodyear, 2013).

On the other hand, when bicyclists want to share pedestrian pathways, they move much faster than the walking or running person and therefore may pose safety concerns. While collisions between pedestrians and bicyclists often result in less severe outcomes, collisions between non-motorized traffic (pedestrians and bicycles) and motorized vehicles tend to result in very severe injury and fatalities. It has been shown that 90% of all bicyclist fatalities are caused by a collision with motor vehicles (Pucher et al. 2011). Naturally, intersections are the place where many of these crashes occur. It is therefore important to study how non-motorized traffic interacts with motorized traffic at the intersection and other roadway areas.

1.2 Research Objectives

The purpose of this research was to build a bicycle simulator and use virtual simulation to investigate how bicycle safety is impacted by interactions with pedestrians and motor vehicles. Specifically, the study examined bicyclists' perceptions and reactions to different situations when riding a bicycle.

1.3 Overview of Research Tasks

To achieve the goal of this study, the research team built a bicycle simulator. Research subjects rode this simulator wearing Oculus Rift goggles to simulate an immersive virtual environment. The virtual environment contained pedestrians, motorized vehicles, as well as different road infrastructure. The researchers collected bicycle rider behavioral data, including looking in different directions, avoiding moving virtual motor vehicles and pedestrians. The rider's perception and reactions to different situations were investigated based on their performance during four virtual simulation scenarios with an electroencephalogram (EEG) readings using a Brain Computer Interface. Various bicycle infrastructure (e.g., bike lane) were simulated to study the influence of each on bicyclist perception and behavior, which in turn have implication on safety. Collected data from the virtual bicycle simulator was be analyzed to identify any behavioral and perceptions related to varying infrastructure. **Figure 1.1** summarizes the tasks performed in this study.

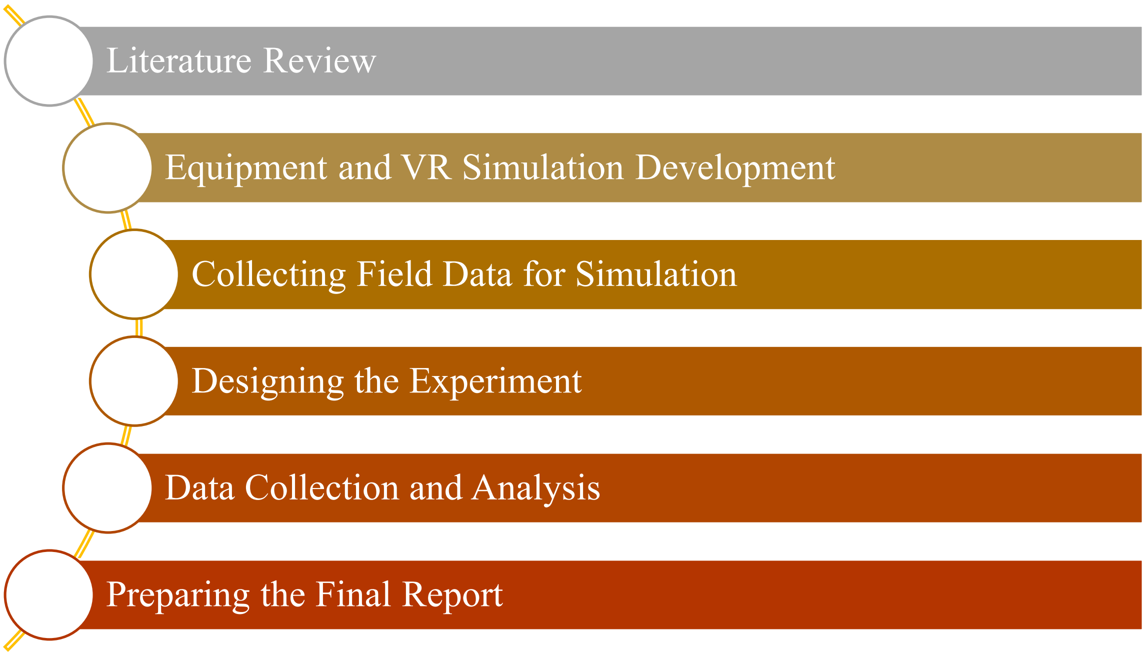


Figure 1.1: Research tasks

2 Literature Review

2.1 Introduction

Recently, there has been an increase in trends to encourage the use of alternative modes of transport, especially active transportation such as bicycling and walking. To ensure the safety of all users, engineers, planners, and decision makers need a greater understanding of user behavior when it comes to mixed modes of transportation. Although the use of bicycles in the United States has become increasingly popular, it is still relatively less compared to the use of motor vehicles. Lack of dedicated non-motorized traffic infrastructure increases the interactions between different mode users as they share the road. The characteristics of mixed traffic on the urban road have a profound impact on the efficiency and safety of traffic (Wang, Zhou, Jin, & Ma, 2015). Romero et al. (2012) explained that there is a direct correlation between cyclists' appreciation of safety and comfort, the volume of traffic, the distance between a bicyclist, and road corridors that decrease as traffic increases (J. Romero, J. Mouram, A. Ibeas, 2012). Safety is one of the major barriers to promoting cycling, especially in urban areas that account for 69 percent of bicycle fatalities each year. Studies have also indicated that intersections are the main conflict areas for mixed modes. For example, 75 percent of all collisions between bicycles and motor vehicles in Massachusetts happened at intersections between 2011 and 2014.

To encourage people to use bicycles, it is important to understand the behaviors of cyclists in a mixed mode environment. Among other approaches, virtual reality (VR) simulations can be used to study the interaction between cyclists and other modes, as well as the interaction between cyclists and the infrastructure. VR simulation can be useful in generating knowledge and data for design purposes and operation of critical road facilities. VR simulation can also be useful in training, rehabilitation, and education programs (Simpson, Johnston, & Richardson, 2003).

2.2 Past Bicycle Simulation Studies

VR simulations have many advantages to researchers, especially in the field of transportation design and traffic operation. One of the most significant benefits of simulation techniques is its potentially low cost for testing alternative designs in a virtual world. However, one major challenge is the difficulty to replicate the real environment in a virtual world. For the results to be valid, VR simulations require the testing environment to be built accurately (Simpson et al., 2003). While there is a significant number of motor vehicle simulation incorporating cycling (e.g., Fournier 2017; & Abou-Zeid 2011), there is a limited number of bicycle simulation studies. For example, Grechkin et al. (2013) conducted a bicycle simulation study in which gap acceptance and intersection crossing behaviors were studied. A series of scenarios were introduced with increasing complexity in one or two lanes and in different directions. Another study focused on short-term changes in gap decisions for adult riders and children and timing of movement in response to public and private transit experiences (Plumert, Kearney, Cremer, Recker, & Strutt, 2011). The same simulation system was used in the Kearney et al. (2006) study to generate traffic at various levels of complexity. The purpose of the study was to understand better how attentional demands and crossing strategies affect gap selection.

2.3 Studying Brain Activity during Biking and Driving

Bicycling can be mentally demanding, especially under complex traffic conditions. Studying brain activity as one rides a bicycle or drives can shed light on human reaction to different driving or riding environments and scenarios. Electrical measurement of brain activity (e.g., Electroencephalogram (EEG)) and computer-based brain scan (e.g., Functional Magnetic Resonance Imaging (fMRI)) are among the methods used to study brain activity (Anderson, 2013). Monitoring brain activity and identifying EEG signals can be done through the neuroheadset electrodes positioned on the scalp. There are many studies discussing the selection of appropriate numbers and locations to put these electrodes on the scalp of the person examined. The changes in the voltage resulting from the ionic current within the neurons are what allow the measurement of brain electrophoresis (Venkatasubramanian & Rajasekhara Babu, 2013).

Although Functional Magnetic Resonance Imaging (fMRI) is deemed to be the most accurate and most visible image for the brain and its activities, Electroencephalogram (EEG) is also commonly used. The fMRI depends on recording changes in brain activity by inferring the change in blood flow in the brain. fMRI is a complement to the brain electric monitoring technique. Despite the real advantages of fMRI, it is relatively hard to use due to the large size of the device and the difficulty of movement of the person to be examined inside this device (Savoy & Ph, 1999).

The early use of EEG devices was made in 1929 by the physicist and psychologist, German scientist Hans Berger, who managed to prove his ability to record the electrical activity of the brain by using a set of electrodes placed on the scalp of the brain (Fabiani, Graton and Federme, 2007). The device invented by Berger to monitor brain layout is described as one of the most spectacular developments in the history of secret nerves.

Wu, et al. (2014) presented an advanced study combining simulation and monitoring of brain signals. The study used a platform moving in a three-dimensional field with a display screen. Also, they used neuroheadset equipped with 36 sensors to monitor brain activity. This study measured brain activity using Event-Related-Potential (ERP), which is one of the significant outputs within the studies of brain signals (Wu, Liang, Lin, & Hsu, 2004).

The mental requirements of cyclists are comparable to the mental requirements of motorists. Similar to motorists, bicyclists need to pay attention, focus, and make a decision as they ride a bicycle. However, while there is significant literature on psychological tests for drivers, information on bicyclists is very limited. While it is possible to benefit from the previous research on the psychological studies of drivers, especially those involving simulation systems, studying bicyclists is important.

2.4 Research Gap

Review of previous literature has shown that many research that used virtual reality techniques (non-wearable) to study the behaviors of motorists. However, a limited number of studies have focused on bicyclists. This study attempts to provide a deep understanding of the behavior of cyclists in a virtual world setting. The modern technologies (simulation and human sensing) allows testing many what-if situations with changing the infrastructure of the roads and conditions surrounding the road user, especially the cyclists. The information collected and analyzed during this study can be used for assessment, planning, building better infrastructure and managing traffic in a manner that supports active transport through cycling and walking. It can be used by municipal agencies to determine the desired improvement, test and improve cycling routes with their interlinkage with pedestrians and cars.

3 Simulator Setup and Design of Experiments

3.1 Simulator Setup

The simulation system was designed and fabricated in the Transportation Research Center for Livable Communities (TRCLC) Laboratory at Western Michigan University. The system includes a platform that embraces the bike with stability supports. **Figure 3.1** shows a picture of the built system. To ensure the stability of the cyclist, the rear wheel was supported by a stationary bike stand. The stand was also used to provide friction to the rear wheel to give a more realistic riding experience. In order to enhance the resistance of the front wheel against lateral movements and reduce the sensitivity of the steering wheel associated with this wheel, the researchers added a rigid cushion and rough surface under the front wheel of the bike. These two additions greatly reduced the vibrations and helped in controlling the movements of the bike and gave the cyclist an immersive experience while riding. A range of virtual reality glasses was also tested to determine the most appropriate for the experiments intended. Virtual reality glasses (i.e., Oculus-Rift) were used in this study.

Figure 3.1: Bicycle simulator setup

Figure 3.2 illustrates the architecture of this system, which resulted in an integrated system that ensures the flow of inputs and outputs smoothly and without any impediments. The following points list the most important electrical processes and programming works:

1. The bicycle was equipped with a rotary sensor on the steering wheel angle and Hall Effect sensor on the back wheel to measure the pedaling torque applied by the bicyclist. Arduino MEGA microcontroller board is used to interface these sensors to the system PC via serial bus working at 115200 baud rates. The information coming from the sensors implement the speed and the direction of the bicycle in the virtual world. Information flow in other direction from the virtual world
2. Flow information in another direction from the virtual world to a bicycle platform using another serial bus. This information includes changes in the virtual road terrain, which gives the cyclist the feeling of these changes in the terrain of the road without the need to move the bike in a three-dimensional space.
3. In the virtual world, a group of cars passes through the main intersection located within the study site. Pedestrian traffic crossing the pedestrian crossing points was also controlled when the cyclist approaches each of the predetermined locations. The first case involves a pedestrian walkway with individual gaps that cross from right to left. The second case involves pedestrian crossing in groups with different gaps between each group and crossing from left to right. These phases were performed using predefined routes and controlled by (C#) programs. These cars were designed to obey the traffic laws to avoid colliding with a bicycle or pedestrian.

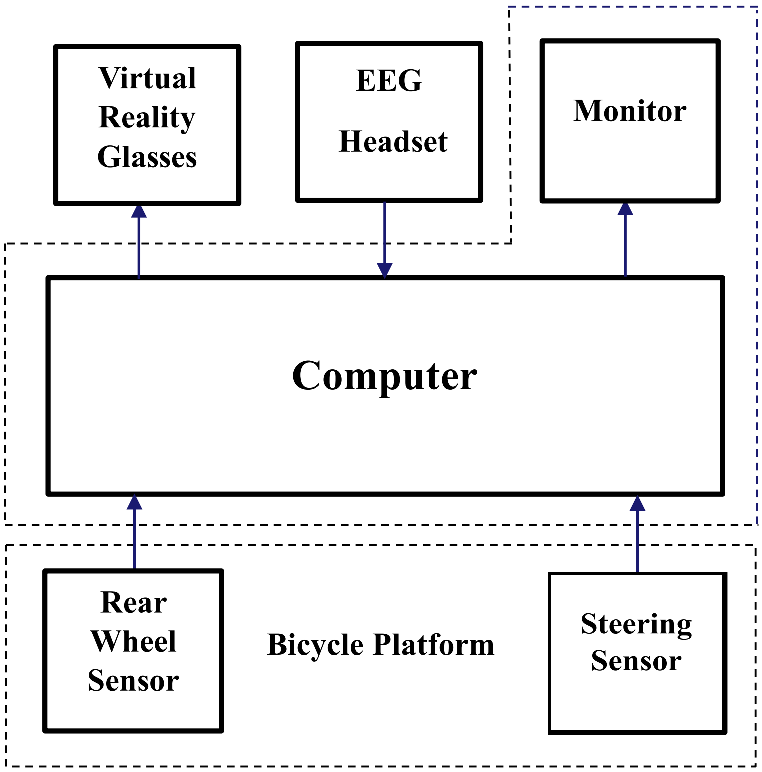


Figure 3.2: Integrated experimentation system

3.2 Design of Experiments

3.2.1 Study Location

The study site was located on the Western Michigan University campus, close to the Student Center, as shown in **Figure 3.3.** It was considered a suitable location for the study, due to the availability of intersections, pedestrian crosswalk, traffic lights, and traffic signs within a short space. The simulation model was built using the 3D Max program, which enabled the provision of road features and great realism both for the different terrain roads in both horizontal and vertical directions. The buildings adjacent to the road, vehicles, pedestrians and other components of the study environment were also modeled. This site is characterized by many activities associated with pedestrians, cyclists, drivers and even public transport users. The Unity Program was used to replicate these activities within the model prepared. It also allowed for change and addition of any new elements deemed necessary for the experiment. Unity's program was linked to Visual Studio in order to allow scripting of the scenarios.

Figure 3.3: Experiment model site

3.2.2 Overview of Scenario Design

The design of scenarios focused on the following main goals:

1. Bicyclist’s gap acceptance behaviors when crossing intersections.
2. Bicyclist’s behavior when merging and sharing a lane with motor vehicles.

3. Bicyclist’s reaction to individual pedestrians at a crosswalk.
4. Bicyclist’s reaction to groups of pedestrians at a crosswalk.

3.2.2.1 Bicyclist’s gap acceptance behaviors when crossing intersections

In this scenario, the bicyclist was expected to stop at a virtual intersection as the intersection had red light signal indication. The intersection had a series of virtual vehicles turning left from a cross street. The subjects were expected to determine a safe gap between virtual vehicles to cross the virtual intersection. The simulator generated virtual vehicles at varying gaps between two consecutive vehicles. The gap that the subjects chose was recorded as well as the time they crossed the virtual intersection. Also, the gaps rejected by the bicyclist were recorded. These were defined as gaps between consecutive cars that passed after the bicyclist had reached the intersection.

3.2.2.2 Bicyclist’s behavior when merging and sharing a lane with motor vehicles.

During this scenario, the bicyclist was required to share a lane with virtual vehicles. The expectation was that the subjects would look for approaching cars before entering the shared lane and that they would position themselves correctly on the virtual roadway lane. These two expected actions were recorded manually during the experiment.

3.2.2.3 Bicyclist’s reaction to individual pedestrians at a crosswalk

The subjects continued to share the road until they came to a virtual crosswalk with individual virtual pedestrians crossing the roadway. The bicyclist was expected to yield the right-of-way to virtual pedestrians already in the crosswalk. The action of the bicyclist in this regard was recorded manually. In addition, the approach speed of the bicyclist as well as the distance from the virtual crosswalk to the front tire of the virtual bicycle when it stopped (if it stopped), were recorded by the system.

3.2.2.4 Bicyclist’s reaction to groups of pedestrians at a crosswalk

This scenario was similar to scenario 3, except that the bicyclist rode around a virtual traffic circle to another virtual crosswalk with a group of virtual pedestrians crossing the roadway. The bicyclist was expected to yield the right-of-way to a group of virtual pedestrians. This scenario had two fundamental differences from the previous scenario: (1) focusing on the interaction of bicyclist and pedestrians moving as a group, and (2) focusing on the interaction of bicyclist and pedestrians when the bicyclist is moving downhill.

4 Data Collection and Analysis

4.1 Introduction

Each subject completed a pre-survey and post-experiment questionnaires. These surveys and questionnaires were used to collect information on the subject's experience with motion (simulation) sickness, their age, gender, riding ability, and their dominate hand. The subject's age, gender, and riding ability were used for statistical analysis purposes only. The subjects dominate hand was needed for association with their EEG data. During the experiment, data was continually collected from the simulation program and stored in Excel files anonymously. These Excel files contained data regarding the subjects actions and locations in the virtual world. TestBench software and EEGLAB toolbox were used to process, analyze, store and display the subject's brain responses collected during the bicycle simulation.

A pre-experiment questionnaire was administered to determine individuals with a history of experiencing motion sickness. This test checked conditions listed in the pre-survey (Appendix 10.3 and 10.4). Individuals who experience these conditions at severe levels did not participate in the experiment. This pre-survey eliminated the possibility of simulator sickness cases among the subjects participating in the experiments. After completing the experiment, a post-stability test and a post- experiment questionnaire was administered to check if the subjects experienced simulator sickness. If the post-survey revealed that the subject had simulator sickness symptoms, the subject was advised to rest for 5 to 10 minutes before leaving the research laboratory.

For each subject that participated in the simulation study, data generated from the bicycle simulation was analyzed using Microsoft Excel. The simulation provided the subject's speed, simulation time stamp, and location of the bicyclist relative to specific points. The location was used to determine distance away from crosswalks, intersections, etc. From the simulation, we were able to relate the time the virtual cars appear in the simulation to the bicycle location to analyze what gaps and position were chosen by the subjects. The EEG data was also collected for each subject and analyzed using EEGLAB toolbox in Matlab. The Matlab toolbox enabled analysis of each subject's brainwaves for given locations to learn how the subject's brain was reacting to each particular event (scenario). Both simulation and EEG data were then combined to allow for the research team to analyze the results.

A total of 41 subjects were recruited for the experiment. However, five of the 41 subjects could not complete the simulation. Therefore, the following analysis results are based on 36 subjects who successfully completed the experiment. Sixty-one (61) percent (or 22 individuals) of total subjects were male and 39 percent (or 14 individuals) are female. Of the 36 subjects who completed the experiment, 33 percent (or 12 individuals) identified as being 25 or younger, while 67 percent (or 24 individuals) identified themselves as being 26 or older. Participating subjects were asked to state their biking skill level. Of the 36 subjects who completed the experiment, 25 percent (or 9 subjects) identified themselves as beginners, while 75 percent (or 27 subjects) identify as experienced. Table 4.1 presents a summary of participants.

Table 4.1: Summary of participants

Gender		
Male	22	61%
Female	14	39%
Other	0	0%
Total	36	100%
Biking level		
Beginner	9	25%
Experienced	27	75%
Total	36	100%
Age		
25 or younger	12	33%
26 or older	24	67%
Total	36	100%

The EEG signals were recorded by an Epoc+ device (from Emotiv) which contained 14 electrodes with two reference points. The accuracy of this commercial type device is relatively acceptable and is designed for research purposes due to its ease of carrying and wearing. TestBench software, which is used to read and record raw EEG data from the Neuroheadset, is also available on the Emotiv website. The TestBench program displays real-time data stream including EEG, FFT, Gyro, Motion, Data Packet, contact quality, and battery level of the headset as shown in **Figure 4.1**.

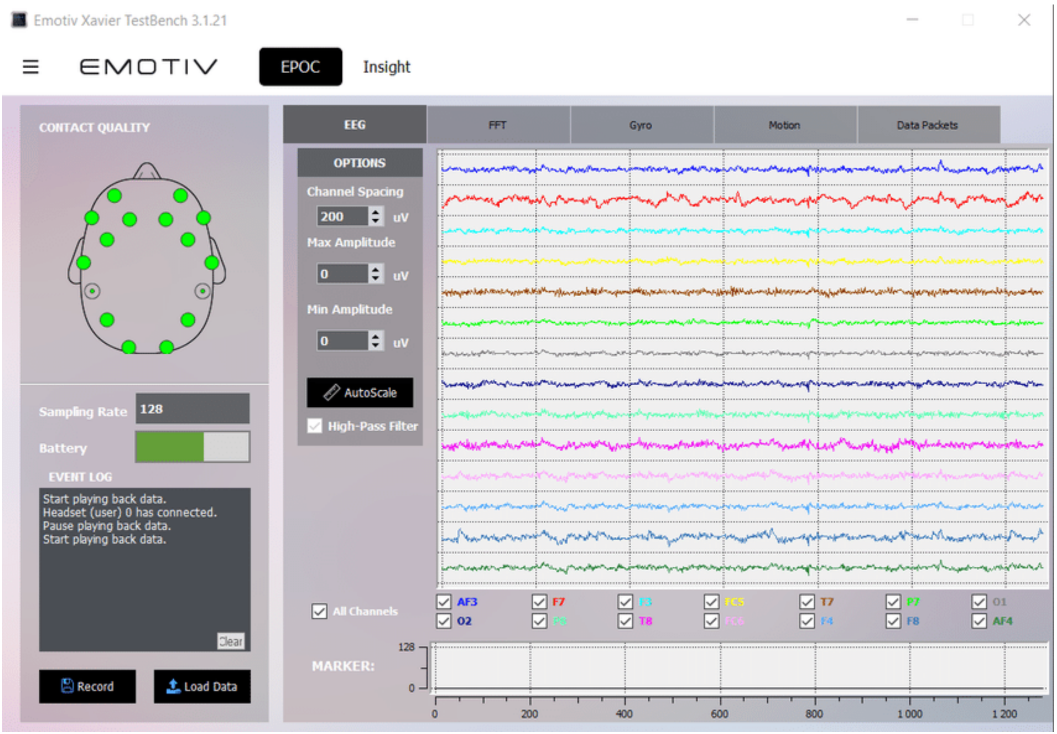


Figure 4.1: TestBench program display

Data recorded during monitoring of brain signals is stored in a standard binary format, EDF. The EDF format is compatible with EEGLab. The sampling rate is 128 samples per second. Names (IDs) and locations of signal electrodes of interest are identified first. The same names and locations of the brain signal electrodes are used in both the recording program and the analyzing program. **Figure 4.2** shows the IDs, numbers, and the locations of the electrodes of the Neuroheadset's device, which is one of the preliminary results obtained from the EEGLab program.

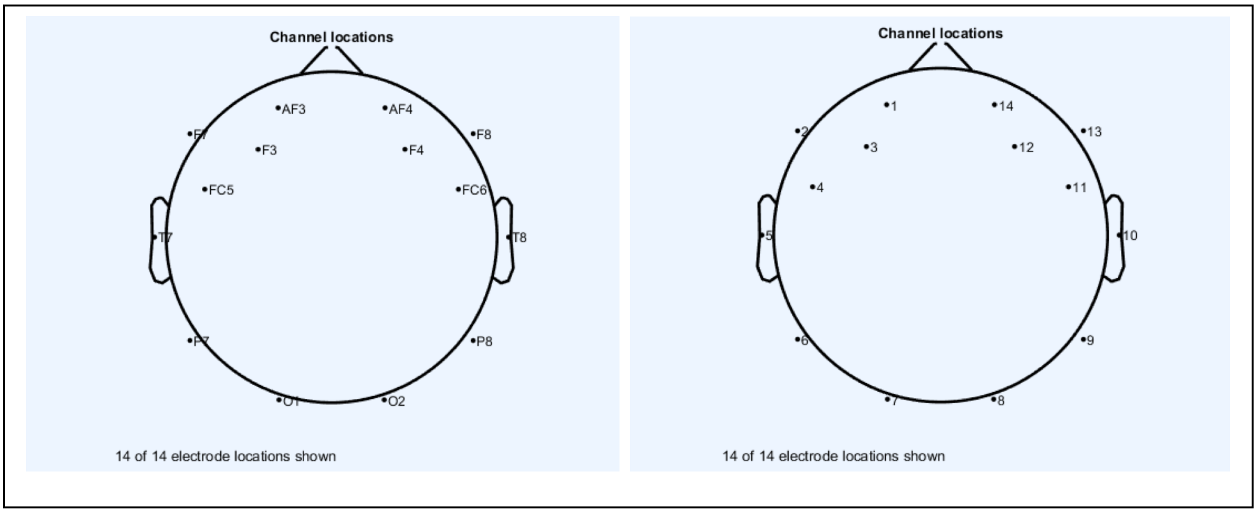
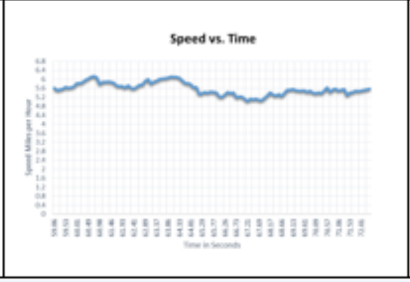
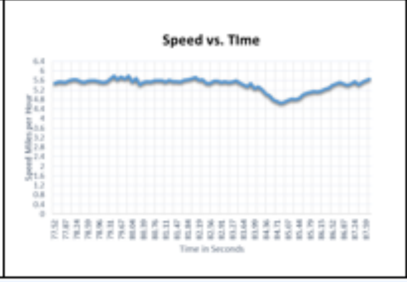
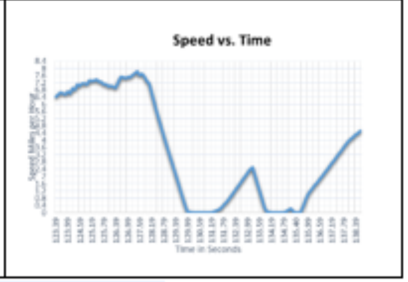


Figure 4.2: Electrodes of the neuroheadset

In our study, brain signals were recorded from all 14 electrodes of the EEG device. The EEG waves (i.e. frequency, location, and amplitude) recorded by electrodes are used to indicate the cognitive state of people. The frequency ranges are used to determine the state of the person in terms of activity and vigilance. Often, the frequencies of more than 8 are for people who are awake and less are for people who sleep or relax. In our study, the frequency range was set from 13 to 39, because the subjects examined were active when riding a bike.

The results from the experiments of this study are the spectrum schemes that show the time-frequency representations of the energy changes in each scenario as well as the brain maps at each important event. **Figure 4.3** and **Figure 4.4** show sample spectrum diagrams of the power and frequency relationship with the time of the experiment and compares it with the time positions of the four scenarios. For the purposes of this study, electrodes AF3, F3, AF4, and F4 were chosen. The reasons for these choices will be explained when addressing data analysis.

Scenario - 1	Scenario - 2	Scenario - 3	Scenario - 4
Time = 29.175 – 55.088	Time = 59.06 -72.01	Time = 77.52 – 87.59	Time = 123.39 – 138.39
			

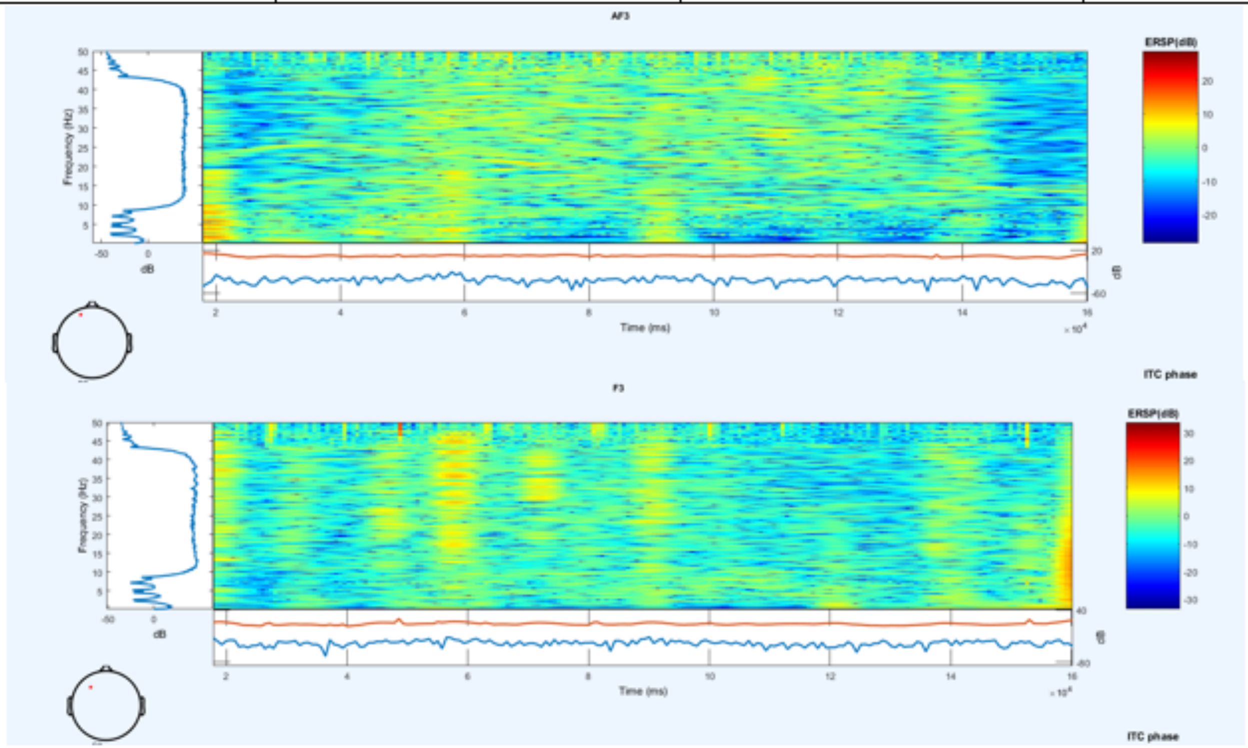


Figure 4.3: Time-frequency for scenarios for electrodes AF3 and F3

Scenario - 1	Scenario - 2	Scenario - 3	Scenario - 4
Time = 29.175 – 55.088	Time = 59.06 -72.01	Time = 77.52 – 87.59	Time = 123.39 – 138.39
			

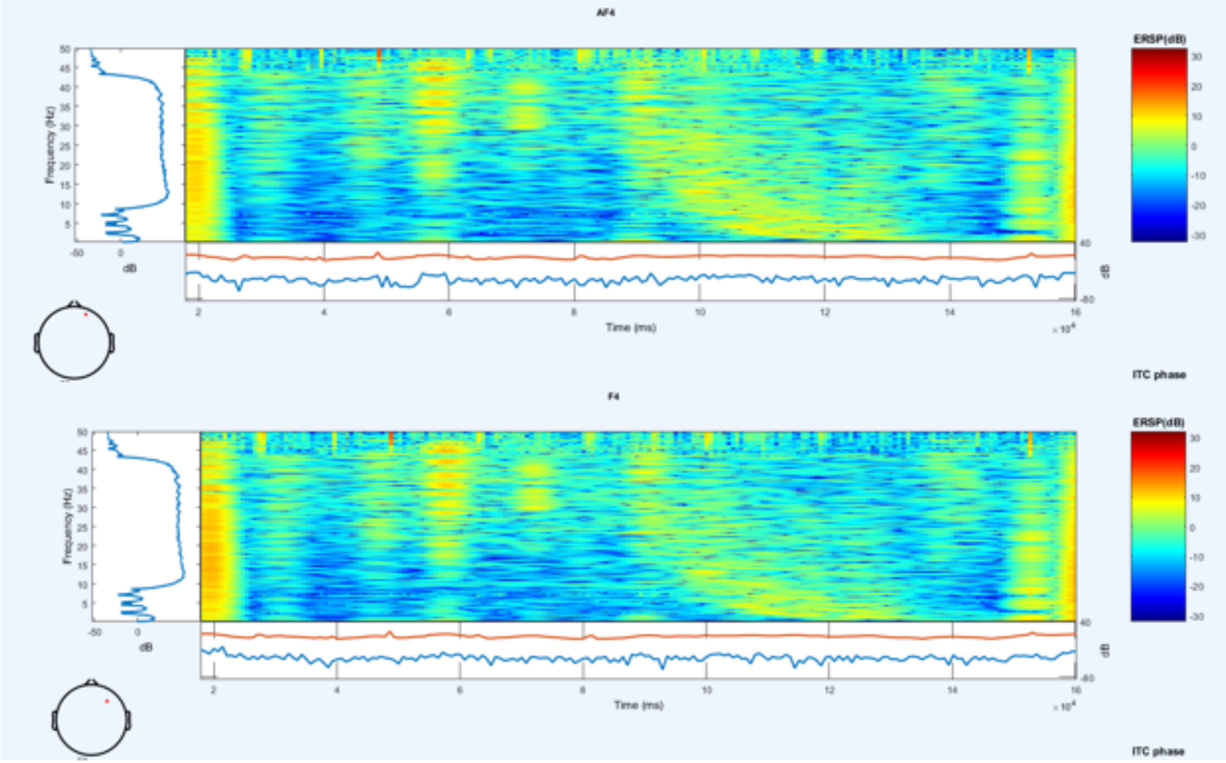


Figure 4.4: Time-frequency for scenarios for electrodes AF4 and FF4

4.2 Analysis of Survey and Simulation Data

The data that is shown in this section is the combination of the following data collection methods.

1. Pre- Survey
2. Manual Data Collection
3. Simulation Output

The results are presented by scenarios.

4.2.1 Bicyclist's gap acceptance behaviors when crossing intersections

For scenario one, each subject's speed was graphed against the distance from the intersection. Such graphs indicated whether the subject stopped or slowed down as they approached the intersection. With red light indication, it was expected that all bicyclists would stop before attempting to cross the intersection. **Figure 4.5** shows that 56 percent (20 subjects) stopped at the intersection, while 44 percent (16 subjects) slowed their speed down. With red light indication, it was expected that all bicyclists would stop before attempting to cross the intersection. When comparing gap acceptance to the subjects who stopped completely vs those who only slowed down, the data show that those who stopped tended to wait longer and rejected more gaps than those who only adjusted their speed as they approached the intersection.

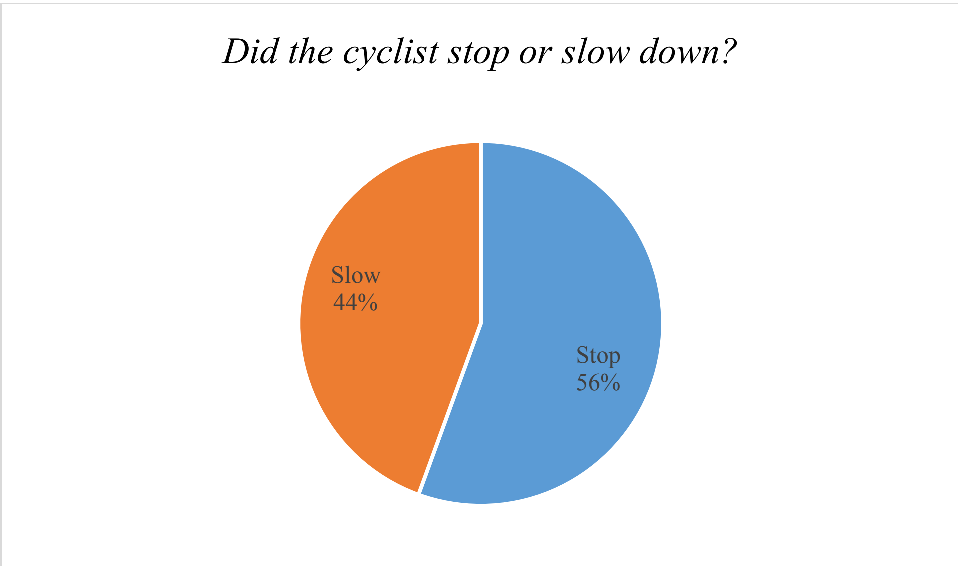


Figure 4.5: Bicyclist's action on approaching the intersection (Scenario 1)

This scenario had cars turning at an intersection with varying gaps between them. The largest gap was 5.16 seconds and the smallest gap was 0.96 seconds. Table 4.2 shows all potential gaps.

Table 4.2: Potential gaps (in sec) available to subjects

Gap6	5.76
Gap7	5.16
Gap8	5.16
Gap9	2.28
Gap10	3.00
Gap11	3.60
Gap12	3.36
Gap13	4.56
Gap14	0.96
Gap15	3.01
Gap16	3.97

In order to visualize what gaps were accepted and what gaps were rejected, the research team recorded if the subject was at the intersection or not when the gap occurred. If the subject was at the intersection and they did not cross, it was recorded as a rejected gap. Gaps were recorded as being accepted when the subject crossed the intersection. **Figure 4.6** shows the distribution of gap acceptance data. The percentages of rejected gaps are out of total rejected gaps. There were 91 rejected gaps and a total of 35 total accepted gaps. The results show that as gap size increase the number of rejected gaps decreased and the number of accepted gaps increased. While the gaps less than 3 seconds were accepted only 9 percent of the time, the gaps exceeding 4 seconds were accepted 36 percent of the time.

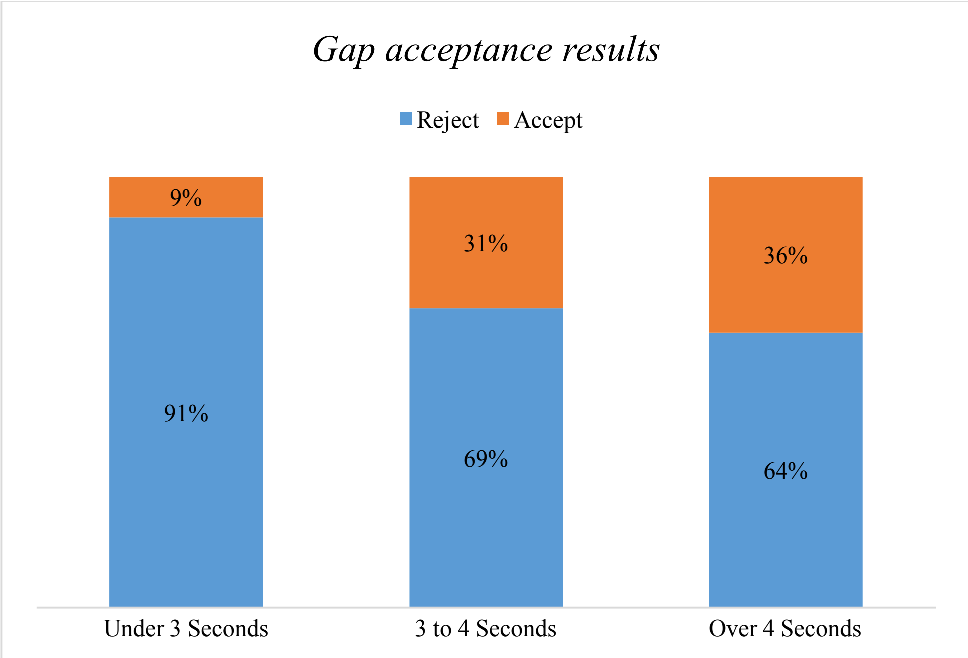


Figure 4.6: Gap acceptance analysis results

4.2.2 Bicyclist's behavior when merging and sharing a lane with motor vehicles

To better understand where individuals are most likely to ride they bike in a shared lane, the research team manual recorded where the subjects spend the most amount of time. The bicyclist's position in a shared lane can have safety implication on both the cyclists and the motor vehicles around them. Shared lanes have pavement markings, popularly known as "Sharrows" that are put minimum 4 feet from the curb to indicate where riders should position themselves. However, this placement varies depending on the road infrastructure. As discussed by Peter G. Furth (2009), these types of lanes can cause many different types of unsafe behaviors. Many motorists feel that they have the ultimate right of way. Bicycle safety is decreased when bicyclist ride too close to the curb motor vehicles feel like they can pass. This is one of the many reasons why there is a push to move the "Sharrows" to be placed in the center of the road.

As seen from **Figure 4.7**, most subject rode in the middle of the shared lane or on the right side furthest from the second lane of traffic. Only 11 percent of the subjects rode closer to the second lane of traffic.

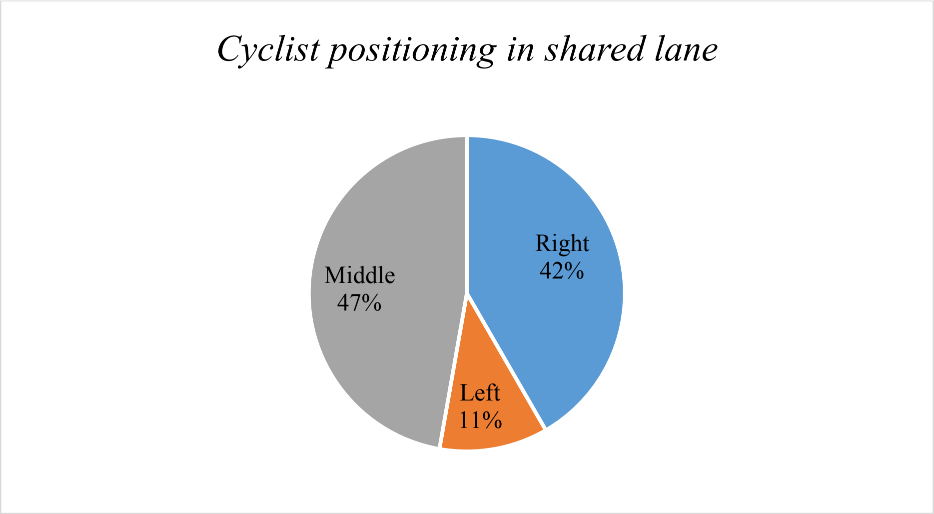


Figure 4.7: Cyclists' positioning in shared lane

Analysis by subject's gender showed that both male and female positioned similarly when riding a bicycle. **Figure 4.8** shows that a majority of each gender rode in the middle of the road, with either the same or a slightly smaller percent riding in the right lane.

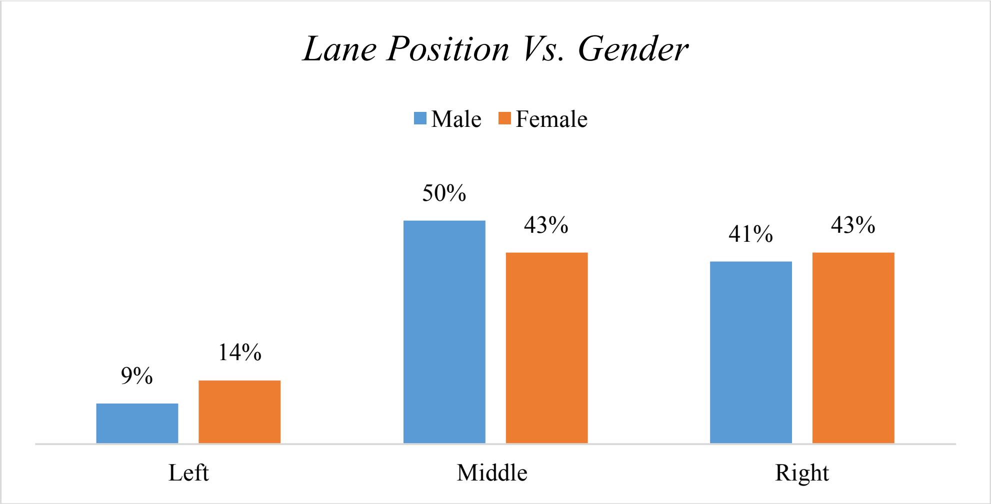


Figure 4.8: Positioning in shared lane by gender

The research team also compared the subjects biking skill level and their position in the shared lane. **Figure 4.9** shows that the majority of beginners (56 percent) rode on the right side of the shared lane compared to only 36 percent of experienced cyclists. Notably, while there was no beginner who rode in the left side of the shared lane while 16 percent of experienced cyclists rode in the left side of the lane.

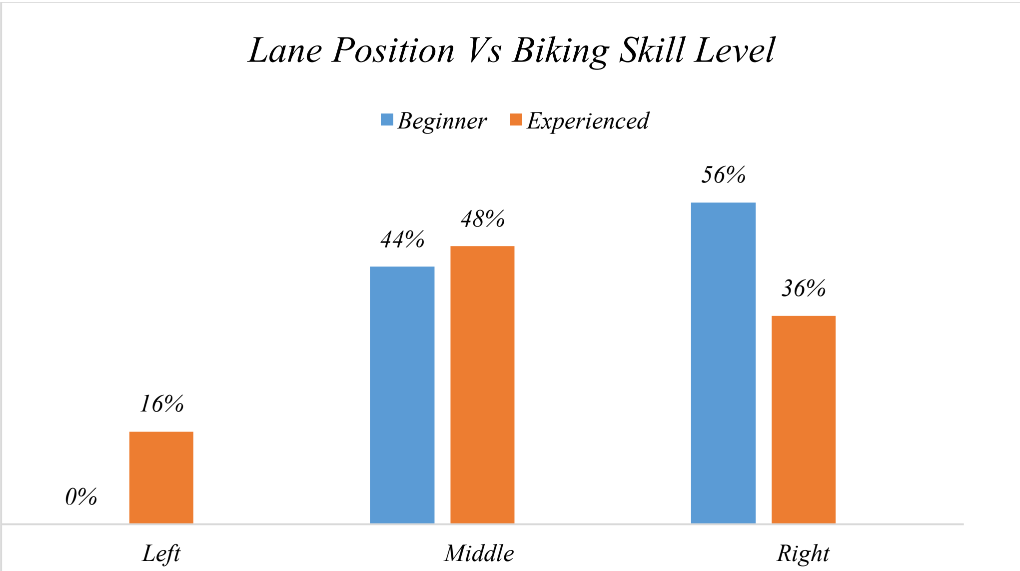


Figure 4.9: Positioning in shared lane by biking skill level

4.2.3 Bicyclist's reaction to individual pedestrians at a crosswalk

For scenario 3, each subjects speed leading up to the crosswalk was graphed. With individual pedestrians crossing the roadway, it was expected that bicyclists would react to the presence of these road users by adjusting their approach speed. **Table 4.3** shows that a majority of subjects (20 of 36) didn't change their approach speed as they approached the crosswalk. About a one-fifth of the subjects slowed and the remaining one-fourth of the subjects stopped. Superimposing speed graphs of all subjects who stopped (25 percent), the average stopping distance was calculated as 11 feet from the crosswalk.

Table 4.3: Action of cyclists when approaching crosswalk with individual pedestrians crossing

Action	Frequency	Percentage
Stopped	9	25%
No Change in speed	20	56%
Slowed down	7	19%
Total	**36**	**100%**

4.2.4 Bicyclist's reaction to groups of pedestrians at a crosswalk

The differences between scenario 3 and scenario 4 were two: (1) focusing on the interaction of bicyclist and pedestrians moving as a group, and (2) focusing on the interaction of bicyclist and pedestrians when the bicyclist is moving downhill. This was done to compare the performance of the bicyclists when exposed to different crosswalk scenarios. As a result, the data was analyzed in very similar ways. In **Table 4.4,** it can be seen that now only eight subjects (22 percent vs 56 percent) did not change their speed while 22 subjects (61 percent) stopped to a group of pedestrians compared to only 25 percent who stopped for individual pedestrians. By superimposing all speed graphs of subjects who stopped, the average stopping distance was found to be 13.1 foot from the crosswalk.

Table 4.4: Speed of cyclists when approaching crosswalk with groups of pedestrians crossing

Action	Frequency	Percentage
Stopped	22	61%
No Change in speed	8	22%
Slowed down	6	17%
Total	**36**	**100%**

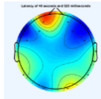
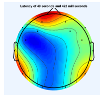
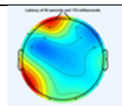
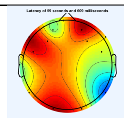
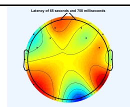
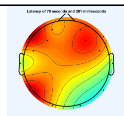
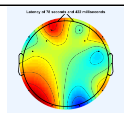
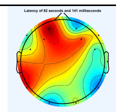
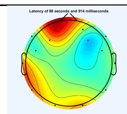
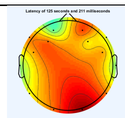
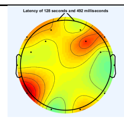
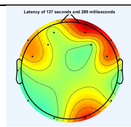
4.3 Analysis of Brain Activity (EEG) Data

One of the objectives of this study was to detect and analyze the cyclic cognitive responses of cyclists to various traffic events. This was achieved by observing the differences in energy and frequency of the EEG signals in each scenario and compare those differences with the age, gender, and skill level claimed by the subjects examined.

Since brain activities are more accurately when analyzed by individual subject, fourteen subjects of the 35 subjects who completed the experiment were selected and analyzed as a sample. These sample subjects included all possible cases for which statistical analysis was possible. Only four front electrodes (AF3, F3, AF4, and F4) were selected. These are electrodes that detect brain activity responsible for focusing, planning, and problem-solving. Riding a bicycle requires focusing, planning, and problem-solving. Not choosing the rest of the electrodes does not mean that they are not involved in the biker's brain activity. However, locations for visual tasks and motor tasks may be more active and more emotional when one is riding a bicycle.

Brain activity analyses were conducted in the before, during and after a specified event/scenario. For example, in the first scenario, time-frequency representations of power changes were determined before entering the intersection, during the entry into the intersection and then after traversing the intersection. **Table 4.5** shows potential cyclist's brain task each scenario. The last column of the table presents sample brain maps for each activity.

Table 4.5: Potential cyclist's brain task in each scenario with sample brain map

Scenario	Time	Potential brain task	Brain Map
	Before	The need to stop before the intersection and pay attention to cars intersecting with the direction of movement of the bike.	
1	During	Paying attention to cars moving in a perpendicular direction with the movement of the bike while traversing.	
	After	Reaching the end of the intersection.	
	Before	Plan to change the path from the bike lane to the shared lane.	
2	During	Attention to cars as the cyclist shares the lane with motor vehicles.	
	After	The need to maintain a consistent track for the bicycle within the lane.	
	Before	Plan to stop or continue to cross the crosswalk.	
3	During	Attention to crossing pedestrians and maneuver to avoid a potential collision.	
	After	The need to maintain a consistent track for the bicycle within the roadway.	
	Before	Plan to stop or continue to cross the crosswalk.	
4	During	Attention to crossing pedestrians and maneuver to avoid a potential collision.	
	After	The need to maintain a consistent track for the bicycle within the roadway	

Data was analyzed for each time-frequency representation values of energy changes for four scenarios as well as variation in age and skill level. **Figures 4.10** and **Figure 4.11** show the relationship between brain activity and age of the cyclist. Results contain details of location (L = Left; R = Right), electrode ID, and event stage (B = Before; A = After). The results in **Figure 4.10** and **4.11** show that energy use was mostly higher for persons aged 26 or older than those age 25 or younger in “before” and “during” stages of events, respectively, especially in scenario 1. This finding suggests that cyclists age 26 and older paid more attention as they rode the bicycle, which could signify more careful bicycle riding. Results in scenario 2, 3 and 4 were not conclusive. The results also show that the right part of the brain often uses more power than the left.

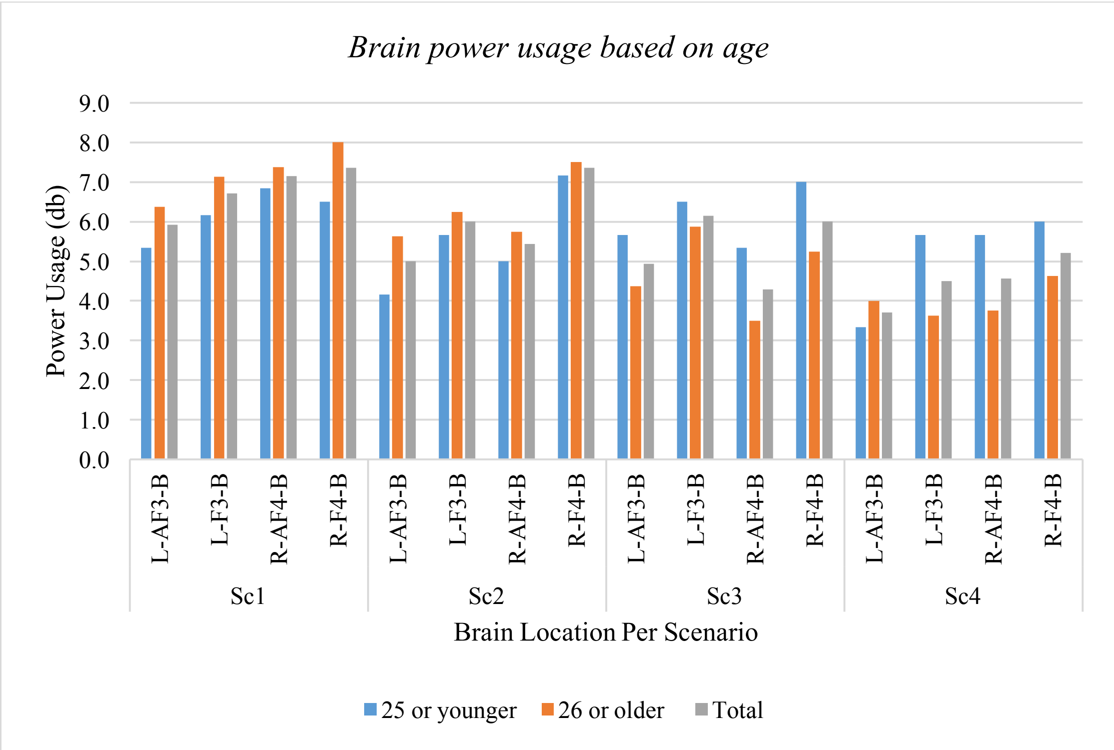


Figure 4.10. Relationship between brain activity and age of cyclist in the “before” stage

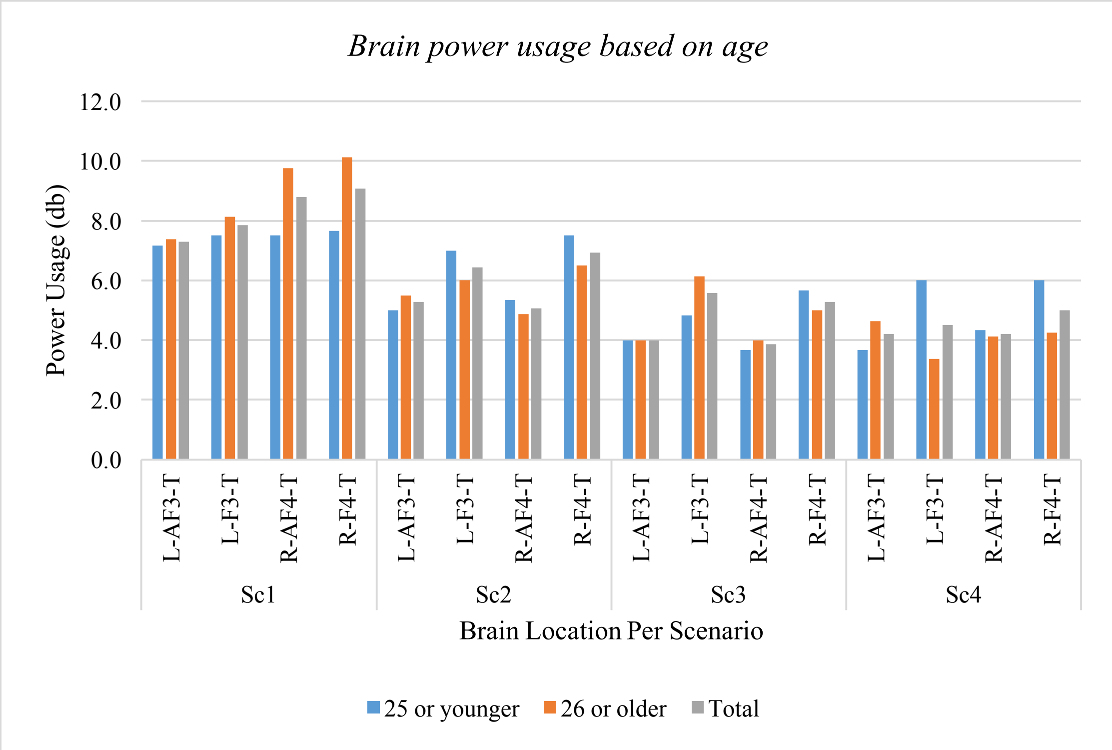


Figure 4.11. Relationship between brain activity and age of cyclist in the "Through" stage

Figure 4.12 and **Figure 4.13** show the relationship between brain activity and the skill level of riders. While results were not conclusive in scenario 3 and 4, results for scenario 1 (Figure 4.12) and scenario 2 (Figure 4.13) show that cyclists who claimed to be experts had lower power usage compared to other cyclists. This suggests that cycling skills have an influence on the perception of cycling environment.

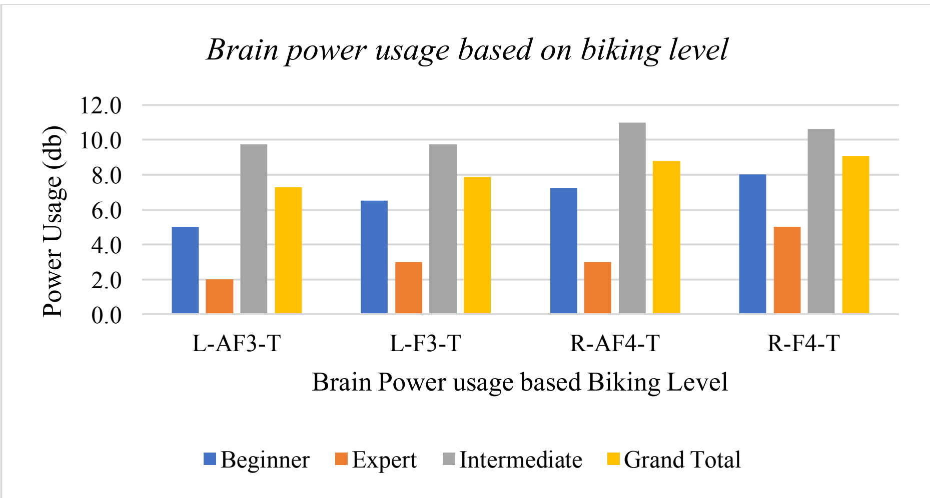


Figure 4.12. Relationship between brain activity and biking level for Scenario 1

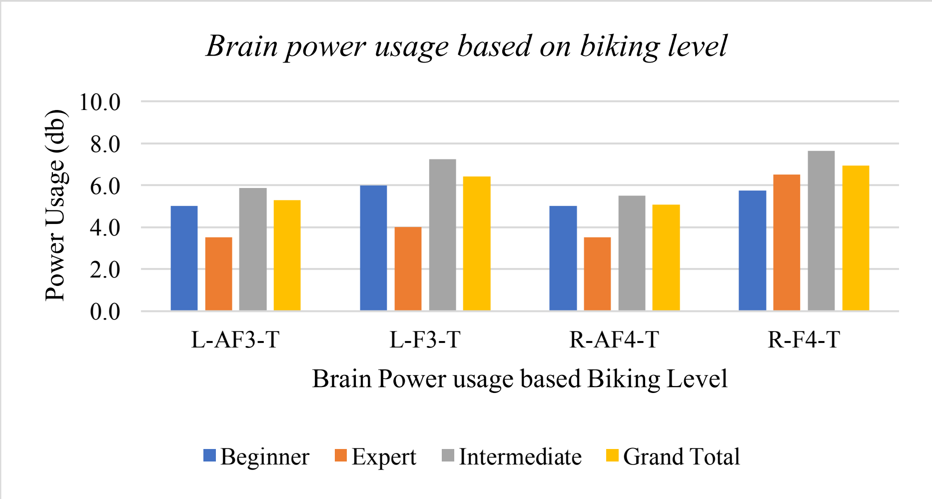


Figure 4.13. Relationship between brain activity and biking level for Scenario 2

5 Conclusions and Recommendations

5.1 Conclusions

This research developed a bicycle simulator that can be used in the future to study cyclist behavior. By using both the Oculus Rift goggles to simulate a virtual environment and the EEG to look at their brain signals, the subject's performance during multiple scenarios was evaluated. The study results indicate that the simulator developed can be used to study gap acceptance. The results also showed that both male and female positioned similarly when riding a bicycle in a shared lane. However, the majority of beginners (56 percent) rode on the right side of the shared lane compared to only 36 percent of experienced cyclists. While there was no beginner who rode on the left side of the shared lane, 16 percent of experienced cyclists rode on the left side of the lane. Analysis of brain activity showed that energy use was mostly higher for persons aged 26 or older than those age 25 or younger in "before" and "during" stages of events, respectively, especially in scenario 1. This finding suggests that cyclists age 26 and older paid more attention as they rode the bicycle, which could signify more careful bicycle riding. Furthermore, the results showed that cyclists who claimed to be experts had lower power usage compared to other cyclists. This suggests that cycling skills have an influence on the perception of cycling environment.

5.2 Recommendations for Future Research

Shared lanes are a huge concern in the biking community. Some bicyclists insist on riding in the middle of the lane regardless of where the signs are placed to increase their visibility. A simulation study to research the vehicles response to the bicyclist riding in different locations would increase and help promote a change to place the signs in the best locations for both the bicyclists and the vehicles may be needed. This driving simulator could be used to measure the distance between the vehicle and the bicyclist. To achieve this, integration of bicycle and vehicle simulator may be important.

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8 Appendix

8.1 Simulation Check List

Simulation Check List

- Explain the experiment
  - Read informed consent form
  - Have them read it and sign if they want to participate (they keep a copy).
- Assign and record unique number on all of their paper work. Unique Number:______________
- Highlight unique number on the master list so we know it has been used.
- Pre - Survey
- Pre - Simulation Sickness survey
- Pre – Stability test (____Sec)
- Set up EEG and Oculus goggles
- Test Ride
  - Delete any output files from the test ride
- Actual Experiment
  - Did they get hit by a Vehicle at the intersection? Yes or No
  - When entering the Shared lane did they look before they entered? Yes or No
  - When in the shared lane were they in the middle of the lane, to the left or to the right? Left Middle Right
  - Did they hit a pedestrian at the first cross walk? Yes or No
  - Did they hit a pedestrian at the second cross walk? Yes or No
- Label their computer file with their unique number
- Post - Simulation Sickness survey
- Post – Stability test (____Sec)

8.3 Pre-Experiment Survey

Please answer the following questions by filling or circling as required

What is your age group: ___<25 yrs ___26 – 65 yrs ___66+ yrs

What is your gender: ____ Male ____ Female ____Other

How do you classify yourself as a biker? Beginner Intermediate Expert

What hand is your dominant hand? Right Left

Please circle the most relevant

Have you (in the past) experienced the following symptoms in the following situation?

While riding a bicycle

1. Nausea:	Never	Sometimes	Often	Nearly Always
2. Head ache:	Never	Sometimes	Often	Nearly Always
3. Dizziness:	Never	Sometimes	Often	Nearly Always

While driving an automobile

4. Nausea:	Never	Sometimes	Often	Nearly Always
5. Head ache:	Never	Sometimes	Often	Nearly Always
6. Dizziness:	Never	Sometimes	Often	Nearly Always

On amusement rides such as roller coaster

1. Nausea:	Never	Sometimes	Often	Nearly Always
2. Head ache:	Never	Sometimes	Often	Nearly Always
3. Dizziness:	Never	Sometimes	Often	Nearly Always

On air travel

1. Nausea:	Never	Sometimes	Often	Nearly Always
2. Head ache:	Never	Sometimes	Often	Nearly Always
3. Dizziness:	Never	Sometimes	Often	Nearly Always

When playing computer games

1. Nausea:	Never	Sometimes	Often	Nearly Always
2. Head ache:	Never	Sometimes	Often	Nearly Always
3. Dizziness:	Never	Sometimes	Often	Nearly Always

8.4 Pre and Post -Experiment Questionnaire

SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions: Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Fullness of the Head	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of
Nausea.