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Human Factors Consideration in Developing a New Drive-by-Wire Interface System

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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Department of Mechanical Engineering
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Sravan Kumar Elineni

Abstract

The current study examined specific aspects of human factors involved in driving a vehicle with a modified Drive-by-Wire (DBW) control system. A DBW system is an electro-mechanical system which controls the primary operations of a vehicle such as steering, acceleration, and braking using a controller such as a joystick. Designing a human interface system for a DBW system involves three main phases in the human factors design process namely user centric/ergonomic design conception, building a prototype and validating the prototype based on human factor considerations. The main objective and focus of this research is to conceptualize a more ergonomic DBW control interface based on human participant evaluations completed in a virtual reality driving simulator equipped with DBW controls. A secondary consideration is the gathering of data for the preparation of a future driver training course.

The driving characteristics of 30 participants consisting of 3 different groups, ages 18-64, ages 65+,and people with disabilities were evaluated while driving with three different controllers: a joystick, a reduced effort

steering wheel plus gas-brake lever combination (GB), and conventional vehicle controls (no Drive-by-Wire or NDBW), which included foot pedals and a steering wheel. The participants were required to drive through different scenarios such as mountain, city, and highway roads, in order to obtain user capabilities related to the steering, accelerating, braking, and compliance with traffic rules.

To examine the steering lane data obtained from the simulator, percent error in lane deviation was calculated and presented against time. The results indicated that the joystick was the most difficult to drive on a straight road. The GB controller was easier to control on straight path maneuvers than the joystick, but it had an over-steering tendency at curves while the joystick was better at curves. To examine group differences of different variables, a one-way analysis of variance (ANOVA) was performed. Results showed that lane position variation, reaction time to brake, reaction distance and stopping distance had significance among variables such as maximum vehicle speed, improper space cushions, and missed turn signals, etc.

Understanding the above characteristics can largely help in the development of a DBW interface system that heavily weighs human factors.

Chapter 1: Research Overview

1.1 Introduction

Independence to perform day-to-day activities is of paramount importance in this growing technological society, and driving a vehicle is an integral part of such independence. Though most individuals take full advantage of driving a vehicle, certain persons with disabilities cannot drive without a modification to the vehicle. Modifications may vary from secondary modifications such as devices to aid in activating the wipers to primary modifications such as a mechanical gas-brake lever. The type of modification needed depends on the individual's upper and lower extremity functional capabilities. One such vehicle modification to drive a vehicle is a Drive-by-Wire (DBW) system. A DBW system is an electromechanical synchronization of the primary control of a vehicle to electronically controlled interfaces such as a joystick to drive a vehicle.

Currently, these DBW systems are commercially available. However, according to user and vendor interviews, it has been noted that mismatches between the driver and the vehicle control system often occur due to poor human interaction design. For example, it is noted from vendor interviews that these DBW systems tend to be quite sensitive and lack marking for the speed bands (refer to EMC© joystick manual (AEVIT Owners Manual)), making them complicated enough to disqualify potential users. Furthermore, lack of proper feedback from road dynamics to the controller and improper postural ergonomics are some of the predominant factors that influence the functionality of the system. As with any new piece of adaptive driving equipment, it requires plenty of training to learn the necessary skills to drive proficiently. More importantly it is necessary for a product to be designed considering human abilities and limitations.

It is proposed that to improve the human-interaction with DBW controls, a prototype controller which incorporates all the ergonomics and driving capabilities of effective steering and braking can be achieved by observing the driving characteristics of participants while driving with their current vehicle modifications. However, since this is not practical and gathering quantitative data would be difficult, a driving simulator is used to collect driving data in a safe, virtual environment. To do this, commercially available DBW control systems are combined with a virtual driving simulator to collect data. Acceleration and braking tests, mountain, city and highway driving simulations help us to better understand human ability and limitations while driving with the controllers. By analyzing the general characteristics of the driving data, specific studies can be designed to target the characteristics of an individual's ability to steer and brake a vehicle. The goal of this study is to provide the groundwork for the development of a new DBW controller interface that better interacts with users. Also a training course schedule is being proposed for potential drivers who use vehicle modifications.

1.2 Research Objectives

The objective of the study is to evaluate the current Drive-by-Wire systems in order to develop a training module and to improve the vehicle modifications considering human factors such as ability of user's steering capabilities. The demand for a better controller takes the research accomplished by Matthew Fowler and Sravan Kumar Elineni in evaluating the driving characteristics to the next level by focusing on the development of a new controller (Sravan kumar Elineni, 2010). On our mission to lay the foundation for a new DBW user interface and driver training course, these summary research questions will be answered.

1) What are the differences in performance among different driving systems?
2) Is there a difference in safe driving practices using DBW controls versus standard driving equipment?
3) How do users perceive the use of the adaptive driving system?
4) What are the human factors affecting the control of vehicle equipped with adaptive driving equipment?

1.3 Thesis Outline

This paper starts with the introduction and thesis objectives in chapter 1, which discusses the need for the development of a new Drive-by-Wire system incorporating all the necessary human factors. Chapter 2 discusses the history of human factors and their importance in product development, as well as current research in related and diverged fields. Chapter 3 discusses the background required to understand the research, including the history of simulators, their use with different assistive driving devices, and current research in automotive and product development considering human factors. Chapter 4 describes different adaptive driving equipment for people with disabilities. Chapter 5 discusses the experimental setup of the test system. Chapter 6 highlights the tests conducted and data collection. Chapter 7 provides the conclusions based on the results and data collected along with suggestions for future work in Chapter 8. Remaining information required to understand this study is included in the Appendices.

Chapter 2: Human Factors

Building human-interactive products is of paramount importance. It not only allows users to interact with the product better but also builds stronger economical growth. As more users can use the product, sales increase, leading to an increase in economic growth. Human factor evaluation is always important to avoid critical misconceptions which might arise in poor design considerations. Human involvement in research should be done from the very beginning of the design process. Feedback should be collected and assimilated at various stages of research. It is also important to consider end users cognitive, behavioral characteristics and physical limitations while designing a product (Kawano, Shibuya, Nagata, & Yamamoto, 1995). At this point a working definition of human factors, the interesting history behind this important study, and human factor involvement in design will be presented.

2.1 Definition of Human Factors

Human factors study is a diverged field encompassing many aspects of applications related to humans. There are many definitions of human factors, the best of which is “Human factors discovers and applies information about human behavior, abilities, limitations, and other characteristics to the design of tools, machines, systems, tasks, jobs, and environments for productive, safe, comfortable, and effective human use." (J.McCormick, 1993)

2.2 History of Human Factors

Machines used by humans are not new, however the consideration of human factors in machine development is relatively new. Many civilizations including the Egyptian used a semi-automatic system for hauling water. The construction technology during those days is largely unknown but systems were surely deployed to construct such magnificent architectural masterpieces. Automatic time-keeping devices have existed since the early 14th century. Jacquard loom, Ure temperature thermostat, the Papin steam safety valve and the Charles Babbage counting machine are some examples of those systems. "But the formal concept of a system as a device to assist human is new, and the concept of man as an important design criterion is even newer". (Research, 1960)

Human factors testing and evaluation of a product design has plenty of historical significance. It was not until the early days of World War II, when new machines and weaponry were deployed for battle, humans were selected and trained to use the system. The systems were also considered to have a lot of mechanical failures. It was not until the time when there was a leap in technology, systems became more complicated to operate and maintain. The United States patent office took special interest in verifying whether the mass produced uniforms and weaponry were a fit for the infantrymen. There was also a greater emphasis on soldiers to be able to load and fire new weapons. Though human factor engineering was years away from being recognized, design engineers were beginning to consider human elements for design considerations.

The post World War II era saw an exponential leap in technology. Due to this change, machinery usage increased, requiring a greater number of personnel to operate and maintain these systems. Until then it was a luxury to select an operator to better operate the machinery but afterwards it was a necessity. It is required that a large group of people be able to use the systems otherwise those systems become obsolete or useless. As a result of this necessity, the relatively newer study, ‘Human Factors Engineering’, emerged. It can be identified as a shift in emphasis rather than the development of a new field (Research, 1960).

2.3 Designing with the Human-in-Loop

Human factors are extant in procedures that are used to design user friendly equipment. For example, flight technologies like S-ETHOS demand a higher rate of design understanding as it involves a higher risk. The S-ETHOS system is a knowledge-based system that interacts with the pilot to analyze his activity while flying and provides feedback in the form of measured appraisal of the errors to improve air safety. S-ETHOS helps air safety experts to simulate real flying and allows them to compare the pilots flying behavior in a controlled environment to real time flying. It gives feedback to the expert about how a pilot assesses each situation (Chouraqui & Doniat, 2003). Human factors are widely used to develop or improvise the existing interfaces in nuclear power plants. It is most important to consider human factors as 99% of operation is normal and boring to operate while 1% of the operation is panicking in power plants. Therefore it is important that the operator has easy access to all the important options to shut down the plant in case of emergency. The design also calls for setting up timed alarms so that the operator stays alert. There is a technological transition in nuclear power plant. The conventional buttons to operate close valves, pumps etc., are integrated into visual touch screen operation. It is of extant priority that human-interaction study be established and a proper interface be developed (Carvalho, dos Santos, Gomes, Borges, & Guerlain, 2008) (Luquetti dos Santos, Teixeira, Ferraz, & Carvalho, 2008).

To effectively build an efficient and reliable system, end users should be included in the design process from the start. The design process involves a series of steps including the need for a new design, concept development, design, CAD modeling, simulation, prototyping, validating the prototype and making possible improvements to the prototype so that it can be produced on large scale to meet customer demands (Staid & Cheok, Human integration in simulation, 1998). Figure 2.3 briefly explains the design process involved in building better human interfaces.

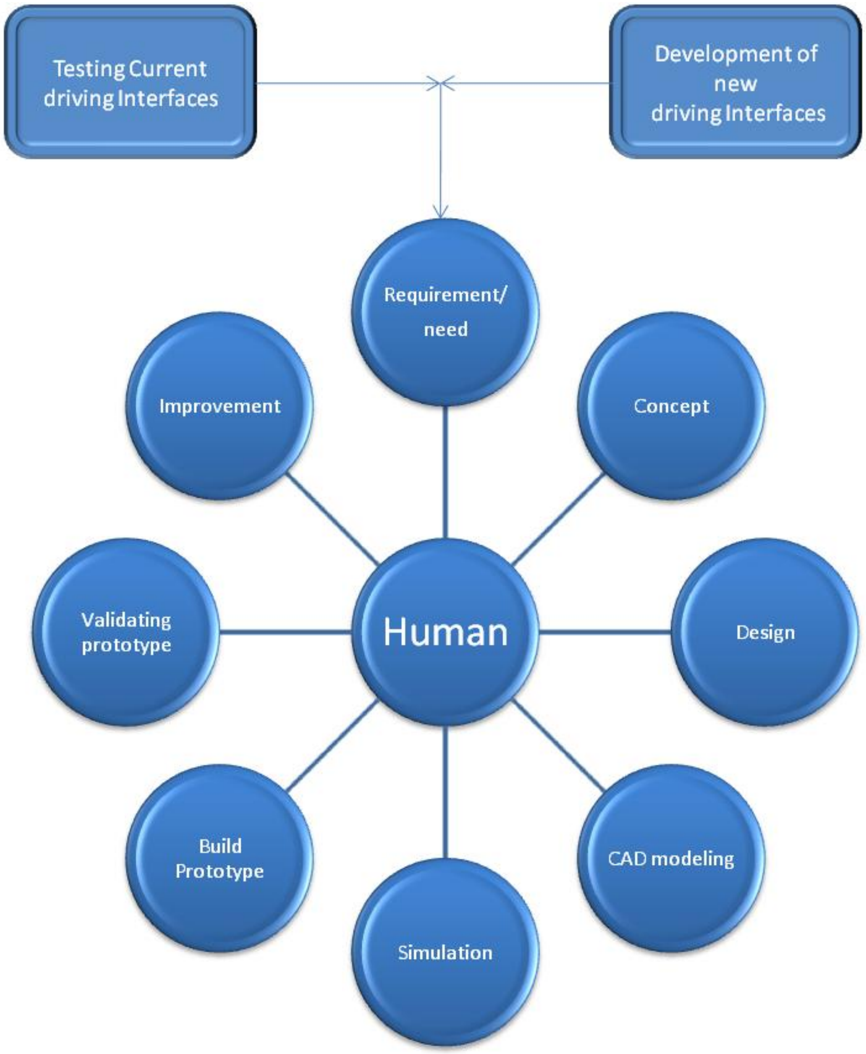


Figure 2.1: Human-in-loop flowchart

2.4 Summary

Although the importance of including human elements and limitations in the design process has a history of more than 60 years, there is still inadequate consideration while designing hardware and software for the next generation. Such oversight can lead to problems in latter stages of the design process. In order to have a better design, research to improve human interactions is done in driving systems, consumer products, electronics, etc. For this project, we are particularly interested in driving, the automotive industry, and the role of human factors.

Human factors engineering accounts for the element of human limitation and characteristics of driving while designing a vehicular system. The interaction among vehicle, vehicle systems, human and the environment in which the vehicles operate are key factors that influence the safety of the driver (Galer, 1995). A research group in Spain constructed a dynamic platform driving simulator incorporating human factors (Maza, Val, & Baselga, 2001). In 2008 Seungwuk Moon and Kyongsu Yi designed a vehicle adaptive cruise control algorithm based on human driving data and appropriate human factors (Moon & Yi, 2008). It is most evident from the above mentioned literature that human factors consideration has gained its importance in much of the automotive research around the world.

Chapter 3: Use of Simulators in Human Factor Studies

Simulators are often used in human interface designing. They provide researchers with such advantages that are otherwise not available. Important design steps, such as collecting research data, safely implementing research tasks that involve risks to humans and repeatability of experiments make simulators a useful tool throughout the design process. Simulators are advantageous in that they eliminate the risks that may exist in the real world while acquiring test data or other specials skills required to operate a driving system. Driving simulators, nuclear power plant simulators, simulators used by NASA, to name a few, are often used to train people and to avoid accidents during the training. Thus these simulators are vital in situations where there is a risk of injury to human participants while performing research tasks.

Beyond eliminating risk of injury during tasks, simulators are extremely useful when designing human interface systems for different consumer products. Simulators allow researchers to collect data in a highly scientific (controlled and repeatable) setting. Having garnered data from human participants, researchers can then analyze the data and find patterns in the human factors related to a person's interaction with the interface, and assess the quality of the interface itself. Combining human interaction patterns and interface effectiveness will allow researchers to highlight a design's strengths and flaws, ultimately leading to design improvements or new ideas altogether.

3.1 History of Simulators

Training for mechanical operation situations has gained importance since the early days of winged aviation. Before they took their first flight, the gliders had some experience of flight, on the ground. The feel for the strong facing wind, yawing, pitching and many other aspects of flying were experienced before flying on actual machines. Thus even before the pilot flew, he had some experience of the lateral controls. In the inception of those early training tools, a synthetic flight training device was devised in the early 20th century. As seen in Figure 3.1, it consisted of two half section barrels mounted on a wooden base and was manually moved to create a feel for pitching and rolling. The pilot had to control the rudder to attain balance while the trainer was moved manually by his friends (Moore, 2008).

In 1929, the cost of learning to fly was high, preventing most of the Americans who dreamt of flying from achieving their goal. Ed Link, the father of the flight simulator was one of them. At that time Mr. Link was working in a piano factory, where his job required vast knowledge of operating pumps, valves and bellows. For his passion in flying, he borrowed some valves and pumps from his father and built a flight simulator which emulated the feeling of flight. This *Trainer* (shown in Figure 3.2) consisted of a blue box which housed pumps, bellows and valves to imitate actual flying

(About.com, 2010). An electric pump drove the bellows allowing the trainer to bank, climb and dive as the pilot operated the control in the cockpit.

Figure 3.1: Synthetic flight training device (Moore, 2008)

Ed Link got his first patent for his Trainer on April 14, 1929, which lead to the invention of later flight simulators for the B-2, F-117 and many other military air-crafts. Although Link's Trainer stimulated the development of modern simulators, it only simulated a feeling of flight. It did not have any visual cues to simulate actual flight. It was not until the development of virtual reality, that the simulators took a more realistic training experience. Douglas Engelbart, a radar technician and an electrical engineer, can be credited for his idea of getting an output of a sequence of binary digits of 1's and 0's onto a digital display so that data can be easily comprehended by the user.

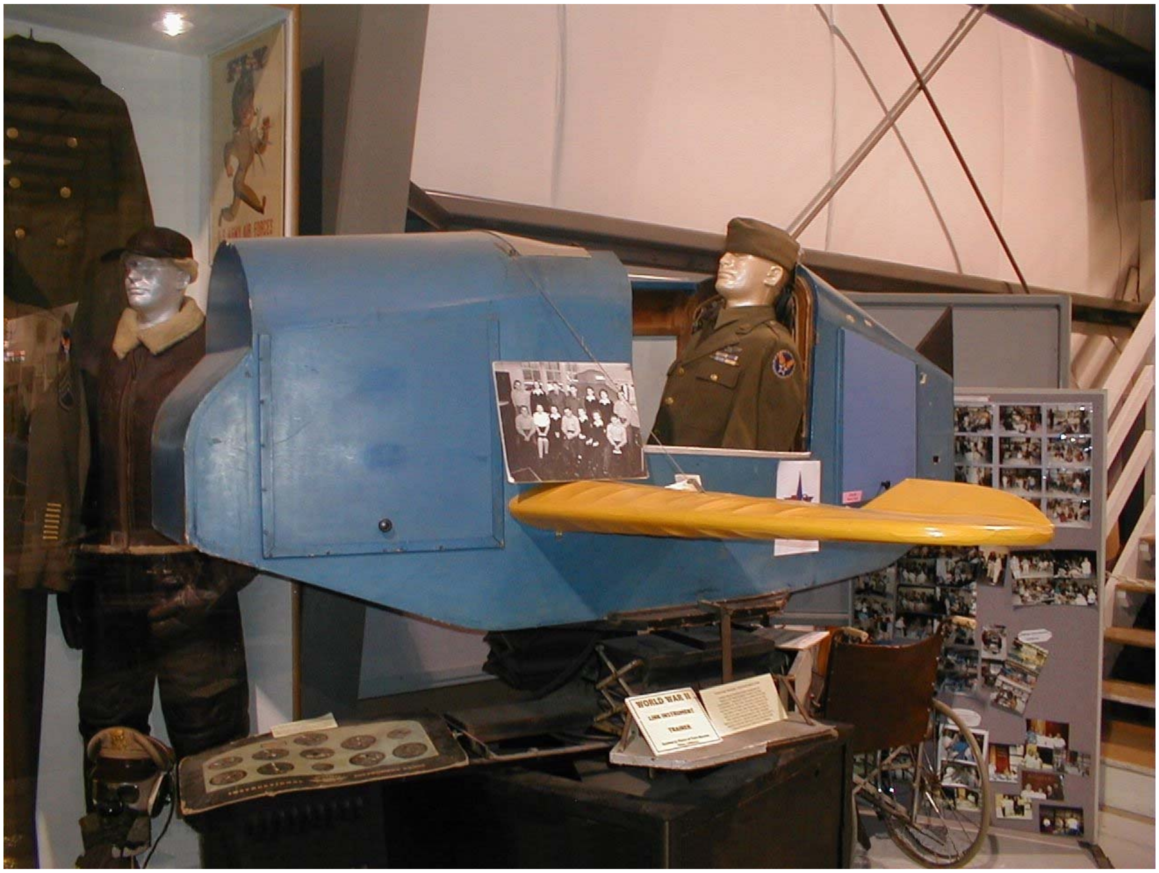


Figure 3.2: Link's trainer (Wikipedia, 2010)

After the invention of the graphical user interface, virtual reality took a leap. Essentially, virtual simulators are simply graphical user interfaces that incorporate a means of control in the form of a controller. After the invention of the graphical user interface, Engelbart developed an “X-Y position indicator for a display system.” The first manipulative device, the “mouse,” was developed in 1964 and patented six years later. The device consisted of a small wooden shell in which two small wheels (one for the x-position and one for the y-position) contacted a flat surface on which the mouse was placed. As an individual moved the mouse, the wheels would roll and change the position of the cursor on the display. With its development, the user could now interact with the display and react to the information being delivered, paving the way for more advanced controllers and interfaces.

In 1968, Ivan Sunderland, with the help of his student Bob Sproull, invented the first virtual reality and augmented reality head-mounted display. Crude in terms of realism, user interface, and graphic display, it was so heavy that it had to be suspended from the ceiling, but was an astounding achievement nonetheless. One of his students, Danny Cohen, would go on to combine the ideas of Sunderland, Link, and Engelbart to create the first real-time flight simulator run on a computer. This coupling of simulators and computers was a vital step into propelling simulators into extremely realistic machines.

With the increase in motor vehicle usage in early 1960s, road traffic accidents have increased dramatically. This fact concerned some of the national governments and vehicle manufacturers. In this advent, vehicle transport safety studies encouraged the use of a safe virtual environment simulator equipped with all the dynamic motions of vehicle to perform safety research. Because of the increase in motorization, the Japanese government began studying driver safety in the 1960s. At that time, the technologies for display and dynamic motions used in flight simulators were not readily available for driving simulators studies (Suetomi, 2008).

Driving simulators are now commonly used in the automotive industry to safely study driving behaviors and test experimental designs. Automotive simulators, in general are used for a variety of driving research around the world. These simulators are commonly used by integrating dynamic force feedback, enhanced presence and dynamic traffic behavior. They are extensively used in vehicular assist system development for safely testing a new system which enhances the driving experience of the users (e.g. Anti-lock braking system), while maintaining comparative standards that would be expected from a real vehicular setup. In addition to the safe environment, it gives researchers an option to make changes to the simulator, overall providing a better platform to test the new device. These simulators also help researchers to observe specific driving behaviors of people so as to predict driving strategies to help prevent accidents.

The significance and use of a simulator in the current project is discussed in the next section.

3.2 Current Research

Virtual simulators are advantageous in that they provide an effective tool for training, and also offer a research evaluation option, which would otherwise not be available for conventional driving evaluation methods. Simulators give the researchers a broad range of compatibility options by the simple addition of a program and without compromising the competitive capability when compared to applications in the real world. (Maria T.Schultheis, 2001)

Simulators are often used in driver safety research for it being a safe and reliable option to test the characteristics of humans like texting messages while driving, which would be otherwise dangerous to observe in real world scenarios. Driving is a complex task which requires simultaneous use of cognitive, sensory, timely judgment and motor skills. It involves interaction with the environment to maneuver with the flow of traffic and avoid obstacles by accelerating, braking and steering (McGehee, Lee, Rizzo, Dawson, & Bateman, 2004). Independence to perform daily routine is of utmost importance. Since driving a vehicle is essential to perform those daily routines, much of driving safety research targets on driving behaviors of senior drivers and drivers with disabilities to keep them and others safe on the roads. Maneuvering safely amongst vehicles involves the understanding of complex parameters, thus making driving safety research an important part of 21st century society. High fidelity driving simulators are used to better understand the driving behavior of people.

In a study by Daniel V. Mcgehee, time required by older drivers and younger drivers to adapt to a driving system was studied using a simulator. It was observed in the study that older drivers steering behavior was more variable than the behavior of younger drivers (McGehee, Lee, Rizzo, Dawson, & Bateman, 2004). In another study by Hoe C Lee, age dependence on driving behavior was studied. In this study, statistical data of traffic rule compliance was collected on a fixed-base simulator and their correlation with age was assessed using regression analysis. It was observed that ability to comply with traffic rules decreased with age (Lee, Lee, Cameron, & Li-Tsang, 2003).

The simulator used in this study is vital to collecting data for multiple reasons. Obviously it would be dangerous to test participants on the roads with other drivers present, because the drivers are unfamiliar with the driving systems being studied. Aside from safety concerns, the study also benefits from a simulator because the trials can be controlled, and data can be more easily gathered. Statistical data measured and evaluated in the study such as distance from the center of the lane and time spent outside the lane would be extremely difficult to measure on streets and highways, but are relatively easy to gather from a computer.

In this research, a rules compliance test was designed to observe the characteristics of different user groups. Number of turn signals missed, inadequate space cushions, and improper lane position are some of the variables measured through the simulator during a highway and city route. This data can be used to observe accident causing characteristics with different controllers for three different groups including individuals between the ages 18-65 years, 65+ years and people with disabilities.

3.2.1 Product Development

Since the main objective of this research is to provide the foundation for a new DBW device, the use of the driving simulator to gather data is justified for this purpose. Among all the different aspects, simulators are known for being a safe and easy option for the designer to optimize the characteristics of the product before it is fabricated (Staid & Cheok, 1998). Good designs have come to rely on simulation as an integral part of design, for it being a safe and an effective tool to obtain important human centered data. It is used in a variety of applications including port design for mariners (Captain W. Frederick Bronaugh), nuclear power plant interface design (Luquetti dos Santos, Teixeira, Ferraz, & Carvalho, 2008) and, most commonly, to design products of day-to-day use.

A computer based design process is advantageous in that most of the testing and optimization is done in a simulated environment. Simulation of the system enables the engineer to better understand the characteristics of the system which helps to validate the performance of the designed system. (Staid & Cheok, 1998) Although product development is unique for different products, automotive mechatronic systems development can be used to best illustrate this process. Vehicle cruise control system, Brake-by-Wire and Steer-by-Wire, are the predominant examples which are designed using a simulated design process.

In 2008, Seungwuk Moon and Kyongsu Yi studied human driving data to design a vehicle adaptive cruise control algorithm. In this study a proposed controller “Adaptive Cruise Control (ACC)” acts as a co-driver assisting the person driving the vehicle to assess the distance between two cars and helps to maintain a safe distance in high speed and stop-and-go (SG) situations. The target of the proposed ACC controller is to understand and utilize standards of normal driving situation to achieve safe vehicle behavior in severe braking situations. The vehicle behavior data collected through sensors attached to a normal vehicle, observes real world driving strategies. They are then used to construct an ACC algorithm using a validated vehicle simulator. The real world data is used to validate the algorithm to simulate realistic driving behavior in stopping strategies (Moon & Yi, 2008).

In another study done by J.H.Lumkes Jr and W.Van Doorn IV, a dual-path front hydrostatic Drive-by-Wire (DBW) system was designed and tested for off road functionality. In this study, mathematical models of the engine and major machine components were used to simulate vehicle behaviors. The results from the physical system were compared to the simulation characteristics to design a DBW system.

In this study, a joystick replaced the steering wheel and propulsion lever which are otherwise used mechanically to control the off-road vehicle. The joystick sends the vehicle control signals to the electronic controller which guides the operation of hydraulic motor to produce a directional motion in the off road vehicle (Lumkes Jr. & Van Doorn IV, 2008). In another study, a fixed-base 14-degree freedom simulator was used to test participants to compare their lane tracking performance using a joystick steering controller to that using conventional vehicle controls. The results from this study concluded that performance of joystick driving largely improved with the addition of force feedback in the controller (Brian, William, & Vivek, 2003).

In the previous chapter, a chart (Figure 2.1) was provided in which the user was the center of the design process. Figure 3.3 illustrates where the user and simulation fit into the product development process. Essentially, simulation is useful throughout any process involving the product development, especially where the user is involved. Product development in general has different aspects to consider including concept, requirement of the product, design, modeling, simulation of the modeled design, validation of the model, and implementation which finally goes into production to and marketing for the end user, the “Human”.

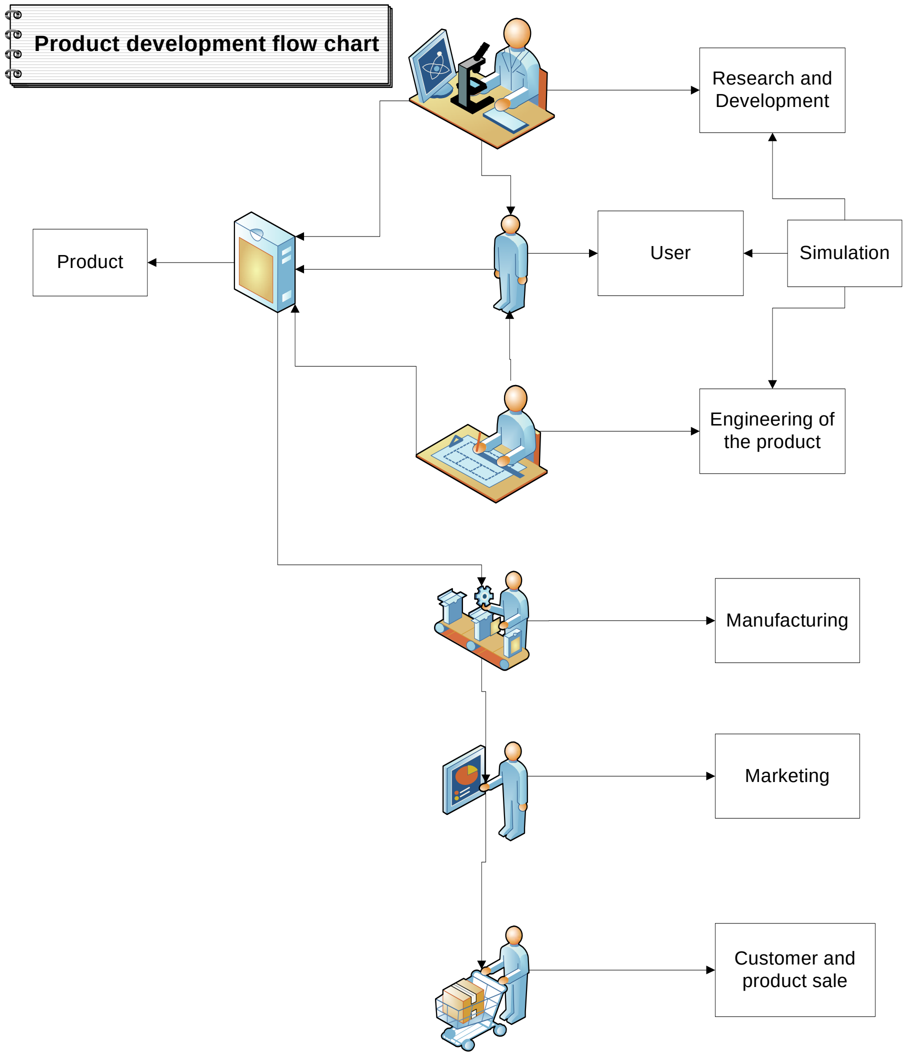


Figure 3.3: Product development flowchart

3.3 Summary

While the use of the driving simulator is essential to this project, it is important to note that some of our simulator design constraints may restrict the driving characteristics of participants. Though characteristics of driving with adaptive vehicular modification can be clearly quantified, data might be influenced by restrictions of our simulator setup. Lack of force feedback, perpetual vision through extended view of sceneries, and poor sound quality, are some items that need improvement. At this point it is important to note that although the simulator setup used here had some disadvantages, results obtained were consistent with each trial and also between each participant. This can be substantiated from the responses noted from the qualitative data collected from survey.

Chapter 4: Key Disabilities and Assistive Driving Technologies

People with disabilities often require some kind of modification to drive a vehicle. Drive-by-Wire (DBW) controls such as a joystick, reduced effort steering wheel are some of the modifications currently used by individuals with disabilities to drive a vehicle. Our point of interest is to design an interactive ergonomic controller. Some currently available assistive devices are presented at the end of this chapter.

Since people with disabilities are the end users of this assistive technology, design consideration should start from understanding the specific human limitations and abilities. So it is important to study common disabilities and their effect on human functionality which may affect their driving capabilities. While injury or disease can affect any age group, there are some disorders that become more prevalent as we age. These are also mentioned as our study population included those individuals ages 65 and up. The following sections explain some of the disorders and their influence on individual driving skills and limitations.

4.1 Neuromuscular Disorders

Understanding the basic neuromuscular disorders and their limitations that prevent individuals from driving a normal vehicle is important while designing a better human interface for them to drive. This section elaborates on some of the neuromuscular disorders which might prevent affected individuals from driving a vehicle. Neuromuscular disorders encompass any disease that impairs an individual's muscular function via nerves. Such disorders can lead to an array of problems, the most debilitating of which is lack of or difficult movement which leads to poor motor skills. Most of these diseases are genetic, but some can be caused by immune system disorders. Amyotrophic lateral sclerosis, multiple sclerosis, muscular dystrophy, myasthenia gravis, and spinal muscular atrophy are all types of neuromuscular disorders, and while they are not curable, most are treatable (Neuromuscular Disorders, 2009).

4.1.1 Multiple Sclerosis

Multiple sclerosis, often abbreviated MS, is a disorder in which a fatty sheath 'myelin' which engulfs axons of neurons in brain and spinal cord is damaged leading to unresponsive signaling from Central Nervous System (CNS) to muscular tissues in the body. MS affects the neurons ability to communicate with each other. MS causes the body's own immune system to attack and damage the myelin sheath. With the loss of myelin, axons will no longer conduct electric pulses that trigger communication between tissues, rendering the subject with partial or complete loss of any function that is controlled by CNS. It can trigger almost any neurological system including changes in sensation (hypoesthesia and paraesthesia), muscle weakness, difficulty in moving, loss of cognitive skills, loss of speech (dysarthria) and other visual problems. MS can largely affect driving ability including the capacity to turn the steering wheel and apply pressure to the brake pedal. Rehabilitation options are available to assist a person suffering from MS. A reduced effort steering wheel, lowered floor van, and zero effort gas and brake through servomotor control are some of the technological options (Wikipedia, Multiple Sclerosis, 2010) to aid those with MS. MS most commonly occurs between the ages of 20 and 40 and is twice as likely to affect women. The disease is also hereditary; if someone in one's immediate family has the disease the likelihood that they too will get MS is one in three, but for the general population the odds are one in a thousand. The disease is most common in Caucasians, specifically those of Northern European descent (Multiple sclerosis, 2009).

4.1.2 Muscular Dystrophy

Muscular Dystrophy, commonly abbreviated MD, is a group of neural disorders that involve muscle weakness of muscle tissue that worsens over time. In the late stages of muscular dystrophy, muscle fibers are replaced by fat and connective tissue. MD can even affect involuntary muscles such as the heart. Person affected by MD can suffer failure in all muscles or only specific muscular segments. It can occur at different ages in one's life. Some affected individuals enjoy normal lives, while others see rapid deterioration of their bodies and die in their late teens. There are nine major types of MD are Myotonic, Duchenne, Becker, Limb-girdle, Facioscapulohumeral, Congenital, Oculopharyngeal, Distal, and Emery-Dreifuss (Muscular dystrophy, 2010).

Myotonic duscular dystrophy, also referred to as Steinert's diseases, is the most common form of MD. The name refers to its symptom, Myotonia, which is a prolonged spasm of a muscle after use. For most afflicted individuals, Myotonic muscular dystrophy causes individuals to slowly deteriorate over their lifetime, leading to a decreased life expectancy. Duchenne is the most common form of MD in kids. Affecting only males, duchenne cause muscles to deteriorate, confining sufferers to a wheelchair. Other symptoms include mild retardation, difficulty breathing, and heart problems. As a result, most children with this disease die in their late teens. Becker is similar to duchenne, but much less severe allowing individuals to walk into their thirties and live much longer into adulthood. Limb-girdle afflicts both males and females and causes debilitation over a twenty year period. Sufferers typically live to mid to late adulthood. Facioscapulohumeral MD causes problem in walking, chewing, swallowing, and speaking. About half of affected individuals can still walk and most have a normal lifespan. Congenital, meaning present at birth, causes not just muscular problems, but also abnormalities in the brain and seizures. Oculopharyngeal, meaning eye and throat, appears in middle-aged men and women and progresses slowly causing difficulty swallowing, choking, and recurrent pneumonia. Distal, a rare form of MD, causes a wasting away of muscles furthest from the center of the body and is typically less severe than other forms of MD. Emery-Dreifuss, another rare form of MD occurring in children and young teens, affects only males. It can cause life-threatening heart problems, but otherwise causes less severe muscle weakness than other forms of MD (Understanding Muscular Dystrophy - the Basics, 2009).

Symptoms summarized:

- Mental retardation
- Delayed development of muscle motor skills
- Difficulty in coordinating between two or more muscles
- Frequent falls
- Eyelid drooping
- Difficulty with walking
- Loss of bladder control

Effects on driving abilities:

- Might have difficulty in turning the steering wheel and applying pressure to the brake pedal.
- Loss of concentration in traffic.
- Inability to use secondary controls of driving like signaling etc.,
- Inability to drive for a prolonged period.

4.1.3 Spinal Cord Injury

A spinal cord injury is the damaging of the soft bundle of nerves that extends from the lower back to the base of the brain. The cord goes through a tunnel formed by the vertebrae of the spine. The spinal cord carries messages between the body and the brain, allowing for movement and feeling, so an injury can greatly impair an individual. Injured individuals are usually paraplegics with no feeling or movement in their legs, or quadriplegics with no feeling or movement in their chest, arms, and legs. Nearly 250,000 Americans have spinal cord injuries. About 52% of spinal cord injured individuals are considered paraplegic and 47% are quadriplegic. Approximately 11,000 new injuries occur each year. Most of the people are males and are injured in vehicular accidents (37%), violence (28%), falls(21%), sports related (6%) and other mishaps (8%) (Spinal Cord Injury Facts & Statistics, 2002). Spinal cord injury is an irreparable damage caused to the spinal cord. It may be due to direct injury to the cord itself or indirect damage to bone tissues or blood vessels surrounding it. The severity of the injury is dependent on the intensity of the trauma and varies from partial to complete paralysis (Spinal cord trauma). This is often the result of a fall, car accident, gunshot, or other accident. Birth defects such as spina bifida can also cause spinal cord issues. Rehabilitation exercises are used to help an individual with an injury regain movement, but they are not always effective (Brain & Nervous System Health Center, 2009). Due to various levels of injury, driving capabilities and restrictions are highly unpredictable. Some might loss all the abilities while others might have good movement in the upper body.

4.1.4 Arthritis

Arthritis is one of the most pervasive diseases usually effecting people over 50 years of age, though it can and does affect all ages. Two primary forms are osteoarthritis, a degenerative joint disease, and rheumatoid arthritis a systemic inflammatory disorder in which the body attacks itself. Arthritis is identified by inflation in the joint with swelling, heat, redness and pain. This can prevent the normal functionality of the joint. The most common symptoms are pain and swelling in the smaller joints of the hands and feet, aching or stiffness of joints and muscles, reduced range of motion in the affected joints etc.

Effects on driving tasks include limited ability to turn steering wheel and difficulty in operating dash controls, turn signals, shift lever, and parking brake release. The effect of arthritis on people's ability to drive can result in license cancellations. Over 1.8 million cancellations were recorded in the year 2000 due to arthritis. Complicating this is that many do not live in areas with good public transportation (Steinfeld, 2010).

4.2 Assistive Driving Devices

4.2.1 Introduction

Assistive driving devices are those devices which allow people with disabilities to drive a vehicle. There are basically two control types, primary and secondary. The function of a primary control is to allow people to operate the vehicle's gas/brake and steering. The secondary control allows a person to use turn signals, head lamps, wipers etc. Adaptive driving equipment is designed and commercially available for people with disabilities. It is also of paramount importance that before modifying a vehicle, the individual should be evaluated and certified by a driver rehabilitation specialist.

Assistive driving devices were in and around for about 30 years. In 1976 Feaver, J.L., Penoyre, S., Stoneman, B.G. worked on developing a Drive-by-Wire vehicle control system for severely disabled Drivers. In this research paper, the reliability problem with the on-board electronic circuits was discussed (Feaver, Penoyre, & Stoneman, 1976). Later, Haynes, N.A., Martin, A.G., Moore, W.R. discussed the hardware and software involved in the development of a DBW system. The hardware used includes electromagnetic clutches, 2:1 timing belts, 18:1 reduction gear boxes, an electronic controller, etc. The electronic controller has three channels, two of which are used to operate the motors and the third channel checks the failure status of the operators and functioning motors. The software consists of three sections: initialization (for calibration and system checks), control algorithm (included data input, output and speed sensitivity) and system test (included inter-processor communication) (Haynes, Martin, & Moore, 1981).

In the recent developments, Zekri, et al. combined the six-degree-of-freedom force reflecting haptic device and commercially available vehicle modification system for better evaluation of people with disabilities. A virtual steering wheel is developed with a haptic device to provide force feedback to the driver (Zekri, Gage, Ying, Sundarrao, & Dubey, 2002).

In 2009, Kameda, Masayoshi Wada and Fujio developed a vehicle joystick control system for wheelchair users with severe disabilities. The main objective of the study was to develop a cost effective driving system for people with disabilities. The design of the vehicle joystick drive system consists of a DC motor, a magnetic clutch, a potentiometer for steering angle detection, and transmission gears. To maintain safety of the vehicle mechanical controls of gas/brake pedal are directly connected to the joystick (Kameda, 2009).

4.2.2 Primary Controls

As discussed in this previous section, primary controls are those that operate the vehicle i.e., steering, accelerating and braking. There are two major categories of primary controls that are commercially available. A cost effective option being a mechanical gas and brake, can be used by only those individuals with upper body strength or paraplegia. Though Drive-by-Wire controls can cost as much as 50-70 times the mechanical controls, DBW can generally be used by people with severe disabilities or quadriplegia.

4.2.3 Mechanical Controls

Mechanical controls are a usually cost effective means for individuals with paraplegia. Mechanical controls are fitted to the car through rigid links. They are advantageous in that they do not prohibit an able-bodied individual from driving the modified vehicle.

Figure 4.1: Mechanical hand control modification (Mobility Equipment-hand controls)

4.2.4 Drive-by-Wire Controls

Drive-by-Wire Controls are sophisticated and often expensive. It is noted from user and vendor interviews that the number of vehicles modified with DBW controls is much less than those with mechanical controls (refer Table 5.1). Also the training process is hectic and requires a large amount of training. These systems best suit those people with quadriplegia (less movement in the upper body) due to their effortless operation. The most common DBW controls include either a reduced effort steering wheel/gas/brake lever or a joystick. Generally, they require very little effort to use them, such as the steering wheel shown in Figure 4.2.

Figure 4.2: Reduced effort steering wheel (Space drive controls, 2009)

4.2.5 Secondary Controls

Adaptive driving equipment used other than to control vehicular maneuvers is considered to be secondary. They include both touch screen and voice activated interfaces. They operate secondary controls of a vehicle such as turn signal indicators, rain wipers, and head lights. They also integrate important safety functions such as automatic engine shut off logic. Some mobility equipment dealers offer interfaces with button-activated controls as shown in Figure 4.3.

Figure 4.3: Secondary control (Econo-console system, 2010)

The vehicle controls used in this study will be presented in the next chapter.

Chapter 5: Human Subject Testing

As discussed earlier, human factor consideration starts from human subject testing. In other words, the product is tested and evaluated by the end users at various stages of the design process. This is a pilot study to evaluate different adaptive driving vehicle modifications. Preliminary driving data from 30 participants were collected in the form of questionnaires and quantitative data from the simulator. The participant groups were divided into three groups: ages 18-64, ages 65+, and people with disabilities. They were required to drive through different scenarios of driving such as mountains, highway, and city driving while utilizing three different controllers including a joystick, a reduced effort steering wheel combined with a gas-brake lever (GB), and a conventional driving controller (no Drive-by-Wire or NDBW).

5.1 System Setup

This driver training and evaluation system is primarily designed to benefit those who have their vehicles modified with DBW controls. The interactive PC-based driving simulator is mechanically synchronized currently with two DBW systems such that the vehicle can be operated while looking at a 3D display of the outside world and roadways. This system design makes it convenient for training people with a variety of adaptive driving control needs.

The DBW or adaptive driving systems are Advanced Electronic Vehicle Interface Technology (AEVIT) controls from Electronic Mobility Controls (EMC©) and are connected to a driving simulator from Simulator Systems International (SSI©), both of which are placed inside a cut away van body, which is wheelchair accessible. A normal vehicle seat is placed stationary on the floor to accommodate participants that are not seated in wheelchairs. The steering column of the SSI system is connected to an electrically powered servomotor through a series of gears and chain drives. The pedal controls of the SSI are connected to another servomotor through a brake wire.

Figure 5.1: Driving simulator system

The combination of these two systems, AEVIT and SSI, gives the driver three options for operating the vehicle. The DBW systems, consists of two controllers to drive the vehicle: a 4-way joystick; and a reduced effort steering wheel/gas-brake lever (GB) combination (see Figure 5.1 for setup of simulator and controls). A driving module interface acts like a central processing unit, mediating between the input from the controllers and output to the servomotors (see Fig 5.2: AEVIT interface). The SSI system can also be operated without the use of the DBW setups by disengaging the lock lever which connects vehicles drive train to DBW system (refer to the thesis submitted by Matthew Fowler for more information (Fowler, 2010)). The SSI system can record performance as the person is driving and provide an overall score. The quantitative data from a steering test with the three different controllers, their comparison with the qualitative data from questionnaires, statistical analysis of acceleration and braking tests, and rules compliance tests are presented in this thesis.

Figure 5.2: AEVIT interface

5.2 Methods

Thirty drivers between 18 and 80 years of age volunteered to participate in this study. Participants were divided into three categories of ten drivers: able-bodied (18-64), elderly (>65) and people with disabilities (ages 23-54) who utilize adaptive driving controls to drive their vehicles. Table 5.1 shows the details about the participants' age and their use of adaptive driving equipment. Eligibility requirements included a valid drivers' license and ability to stay seated for about 3 hours. Each participant was assessed during a 30-minute initial interview. This interview was conducted to take study consent signatures as required by the USF-IRB (approved IRB#107994) and to collect driving related information from each participant. After the initial interview and consent process participants were asked to sit inside the simulator setup. The setup consisted of a cut shell of a standard van. A common vehicle seat was used by people who do not use wheelchairs as a mobility device. Figure 5.3 shows the experimental setup.

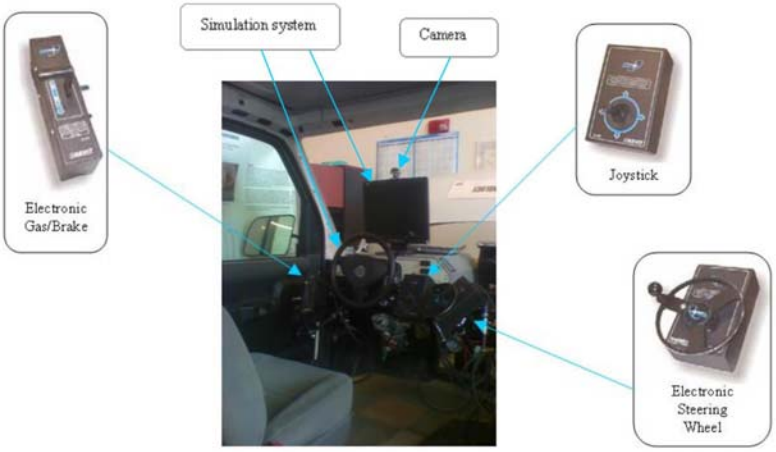


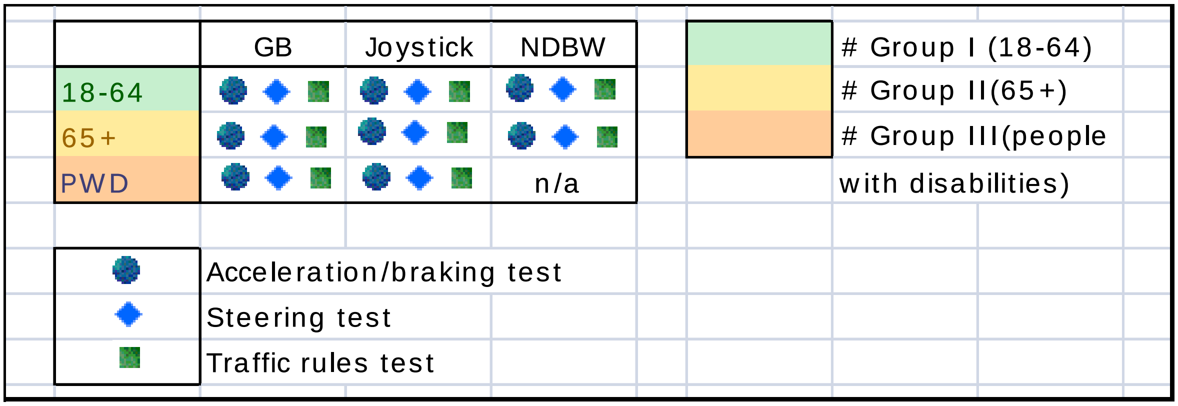
Figure 5.3: AEVIT DBW system connected to simulator system SSI

Table 5.1: List of participants

	S.no	Age	Condition	Use of assistive driving devices
Group I	1	24	right-handed	Does not use any adaptive driving equipment
	2	40	right-handed	Does not use any adaptive driving equipment
	3	54	left-handed	Does not use any adaptive driving equipment
	4	25	right-handed	Does not use any adaptive driving equipment
	5	35	right-handed	Does not use any adaptive driving equipment
	6	23	right-handed	Does not use any adaptive driving equipment
	7	50	right-handed	Does not use any adaptive driving equipment
	8	48	right-handed	Does not use any adaptive driving equipment
	9	36	right-handed	Does not use any adaptive driving equipment
	10	25	right-handed	Does not use any adaptive driving equipment
Group II	1	71	right-handed	Does not use any adaptive driving equipment
	2	65	left-handed	Does not use any adaptive driving equipment
	3	73	right-handed	Does not use any adaptive driving equipment
	4	69	right-handed	Does not use any adaptive driving equipment
	5	72	right-handed	Does not use any adaptive driving equipment
	6	75	right-handed	Does not use any adaptive driving equipment
	7	67	right-handed	Does not use any adaptive driving equipment
	8	69	right-handed	Does not use any adaptive driving equipment
	9	80	right-handed	Does not use any adaptive driving equipment
	10	79	right-handed	Used DBW adaptive driving equipment
Group III	1	27	right-handed	Uses mechanical adaptive driving equipment
	2	49	right-handed	Uses mechanical adaptive driving equipment
	3	26	right-handed	Uses mechanical adaptive driving equipment
	4	40	right-handed	Uses mechanical adaptive driving equipment
	5	34	left-handed	Uses DBW adaptive driving equipment
	6	45	right-handed	Uses mechanical adaptive driving equipment
	7	19	right-handed	Uses mechanical adaptive driving equipment
	8	55	left-handed	Uses DBW adaptive driving equipment
	9	48	right-handed	Uses mechanical adaptive driving equipment
	10	58	right-handed	Uses mechanical adaptive driving equipment

In the Table 5.1, 18-64 years, 65+ years and people with disabilities groups are represented as Group I, Group II, Group III respectively. The test was conducted for approximately three-hours. During the test the participants were videotaped from two different angles: a face view – to record facial expressions and a side view – to record foot and hand movements. These tapes are preserved for review of the driving characteristics of individuals. Three tests were conducted as a part of the study. Data from acceleration and braking test, steering test and rules compliance test were then used to design a driver training course and to improve the present adaptive driving controllers. The green color represents 18-64 years group, 65+ years group with yellow and people with disabilities group with orange. The circle, diamond and square represents acceleration/braking, steering, traffic rules tests respectively.

Table 5.2: Description of tests and controllers



	GB	Joystick	NDBW
18-64	● ◆ ■	● ◆ ■	● ◆ ■
65+	● ◆ ■	● ◆ ■	● ◆ ■
PWD	● ◆ ■	● ◆ ■	n/a

🟩	# Group I (18-64)
🟨	# Group II(65+)
🟧	# Group III(people with disabilities)

●	Acceleration/braking test
◆	Steering test
■	Traffic rules test

Table 5.2 visually represents the different tests administered to each group. The controller usage was randomized for each person in the beginning of the test. Random numbers were selected using an online source (Plous, 2008). For example if 1 represents joystick, 2 GB (Gas/brake system) and 3 NDBW (no Drive-by-Wire), and a user was randomly selected to use controllers in the order of 1, 3 and 2, the joystick controller was used first followed by NDBW and lastly GB controller respectively. The participants

were asked to discontinue at anytime in the occasion of a discomfort such as fatigue or simulator sickness.

The participants were then given a brief overview of the functionality of the controllers before they were operated. Also clear audible instructions were given for the route instructions.

Instructions for the reduced effort steering wheel:

1) Clock-wise rotation causes the vehicle to turn right
2) Counter-clockwise rotation causes the vehicle to turn left

Instructions for the gas/brake lever:

1) Pushing the lever forward causes the vehicle to accelerate
2) Pulling back on the controller causes the vehicle to decelerate

Instructions to operate the joystick:

1) Pushing the lever forward accelerates the vehicle.
2) Pulling back on the joystick causes deceleration in the vehicle.
3) To turn right, push the joystick to the right.
4) To turn left, push the joystick to the left.
5) To make small adjustments in the lane, tap the joystick in respective directions.

5.2.1 Acceleration and Braking Tests

The acceleration and braking test was conducted on the test participants with all appropriate controllers. The test was conducted three times for data accuracy and they were averaged for results. Before starting the test, participants were given instructions to start the vehicle (simulator) and accelerate up to 50 mph and brake as soon as a red stop sign appeared on the middle of the screen. They were instructed to hold the brake until the vehicle came to a dead stop (refer to Figure 5.4).

Explanation

Accelerate up to 50 mph
and then brake when you see this sign.

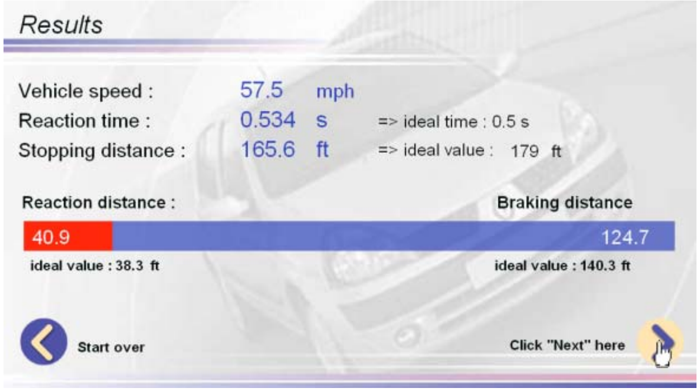
Figure 5.4: Acceleration and braking instructions

0 mph

Start your engine and accelerate to 50 mph.

Figure 5.5: Vehicle position in acceleration and braking test

Figure 5.6: Stop sign displayed



Results

Vehicle speed : 57.5 mph
Reaction time : 0.534 s => ideal time : 0.5 s
Stopping distance : 165.6 ft => ideal value : 179 ft

Reaction distance : 40.9 ideal value : 38.3 ft
Braking distance 124.7 ideal value : 140.3 ft

Figure 5.7: Sample results page

Figure 5.5, 5.6 shows the actual test screenshots. Figure 5.7 shows the results page displayed after finishing each trial of test. To get acquainted with the controller, each participant was given a trial run before beginning the actual test. The quantitative results of reaction time, stopping distance etc., were displayed on the screen following the test and are recorded.

5.2.2 Steering Capabilities Test

The steering test was administered on a mountainous road with no traffic. The route was composed of straight maneuvers and curved paths. The controller's reaction to maneuver a curved path was primarily tested. Figure 5.8 shows the straight path in steering test. Figure 5.9 shows a curved path maneuvering.

Figure 5.8: Steering test - straight line

At the beginning of the test, the participants were given clear audible instructions. The first part of the test was a straight line maneuver and required that the participant stay within the acceptable lane limits. Following the straight maneuver is a curved path where the participant had to comply with posted speed limit to make an appropriate turning maneuver.

Figure 5.9: Steering test - curved path

The collected data is saved as a text file by the simulator program. The data is represented with lane positions and lane widths recorded for every 0.2 seconds. The data is graphed and shown in Appendix A. It is also evaluated using a C++ program (refer to results section for more information on C++ program and its usage). The program gives us the information of time spent outside the lane and number of turns to the left and right (refer to Appendix C). Throughout the course, speed limits were posted on clear white boards on the side of the roads. The speed limit at the beginning of the test is 30 mph (straight road) (refer to Figure 5.8) and is reduced to 20 mph at the curved path (refer to Figure 5.9).

5.2.3 Rules Compliance Test

In this test, the ability of the participants to comply with traffic rules is tested. City and highway routes are virtually simulated. The simulator tracks study parameters like improper space cushions (inappropriate distance from the front vehicle), improper lane changes (represents number of wrong lane changes due to lack of control on vehicle), and turn signals missed. The simulator also presents us with a compatibility option through which the structure parameters of traffic, weather, and visibility could be set. In this test the traffic is set to minimum and weather to be clear sunny day. Refer to Figure 5.10 for city and highway routes. The picture on the left depicts a city and the one on right depicts a highway.

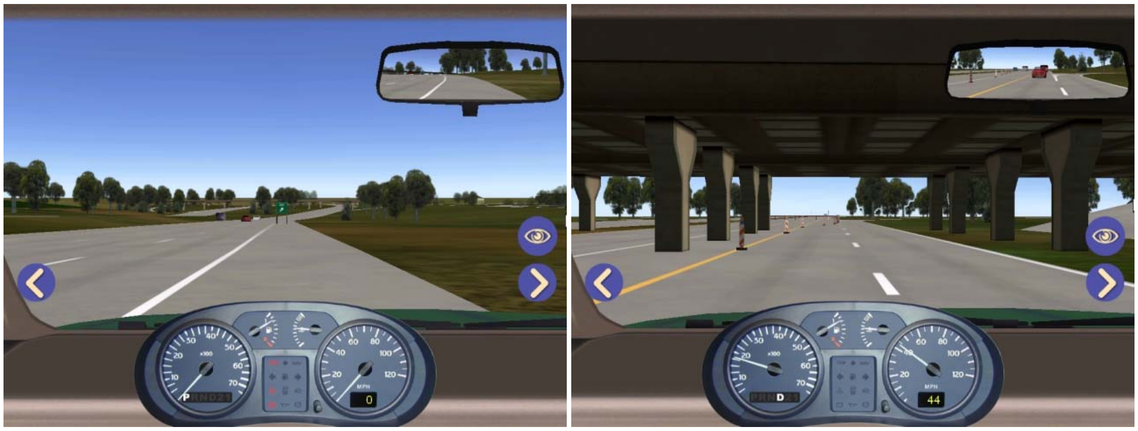


Figure 5.10: City (left) and highway (right) routes

5.2.4 Driving Performance Questionnaire

Performance surveys form a strong basis for human factors evaluation if designed in a proper manner. In this survey, the participants were asked questions regarding the controllers' performance before and after each test. The opinion of the participants on specific details of system safety, ease of learning to use, system ease of use, system reliability, their ability to control gas/brake, their level of confidence, ease of operation, proficiency and realism in each scenario were recorded. They were also asked to rate on a scale from one to five where one (1) being unable to five (5) being easily able to complete a task. They were also required to answer the same question in detailed text. Lastly, a comparison survey was conducted for able-bodied younger and older participants. They were asked to compare standard equipment to the adaptive driving equipment. Questions to compare the systems were also asked.

Chapter 6: Results and Discussion

Results can be characterized into two groups, quantitative and qualitative. Quantitative data can be analyzed statistically to validate the purpose of the experiment whereas qualitative data helps us to design an ergonomically improved driving system. The qualitative data from the questionnaires yielded responses about the participants' ideas, views and their scaling on different aspects of driving with the controllers. Quantitative data collected from the simulator in the form of lane variation, reaction times, stopping distances, braking distances, inadequate space cushions, inadequate lane maneuvers help us to statistically analyze the performance of the controller and build a better human interface for the DBW driving controllers.

6.1 Evaluation of Acceleration and Braking Performance

As previously noted, GB stands for gas-brake system used in conjunction with a small steering wheel, and NDBW stands for no Drive-by-Wire system (conventional car control). In a previous thesis submitted by Matthew Fowler (Fowler, 2010), he discussed the differences in various parameters such as maximum speed, reaction time and braking distances when driving with different controllers. The information presented included comparisons of reaction times, maximum speeds and braking distances between different groups while driving with different controllers (Fowler, 2010). In this paper, statistical analyses were performed using Analysis of Variance (ANOVA) in Excel 2007 to validate the significance of the different experimental variables: reaction time, stopping distance, maximum vehicle speed, reaction distance, and braking distance (stopping distance = reaction distance + braking distance). In the analysis *SS* stands for sum of squares, *df* for degrees of freedom, *MS* for mean square. ANOVA *F* statistical value is calculated by

$$F = \frac{MS \text{ between groups}}{MS \text{ within groups}}$$

The derived *F* value from the experiment is then compared to *F* critical (*F crit*) value to determine significance between groups.

Table 6.1: ANOVA results for reaction distance

ANOVA summary of reaction distance						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9006.32268	2	4503.16	23.012227	1E-08	3.1154
Within Groups	15067.791	77	195.686			
Total	24074.1137	79				

From the Table 6.1, values of *F* and *F crit* can be noted as 23.0122 and 3.1154 respectively. Since the *F crit* value is much less than the calculated *F* value, the variable reaction distance has significance between the three groups. With acceptable significance being 0.05 or 5 % probability of non occurrence (p<.05), the level of significance can be further verified using *F crit* value of 0.01 significance. *F crit* value for .01 significance (p<.01) can be calculate from the Table D.1 in Appendix D. *F crit* values for *df* =70 and *df* =80 are 4.92 and 4.88 respectively. To find an *F crit* value for *df* within groups of 77 is as follows:

$$F\ crit_{0.01} = 4.92 - \frac{(4.92 - 4.88) * 7}{10}$$

$$F\ crit_{0.01} = 4.892$$

Since the calculated $F\ crit_{0.01}$ is constant for *df* =77, the calculated *F* value of 23.012227 is greater than $F\ crit_{0.01}$ value showing valid significance with $p<0.01$.

Table 6.2: ANOVA results for reaction time

ANOVA summary of reaction time						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.67857317	2	0.83929	16.232716	1E-06	3.1154
Within Groups	3.98116168	77	0.0517			
Total	5.65973484	79				

From the Table 6.2, values of *F* and *F crit* can be noted as 16.232716 and 3.1154 respectively. Since the *F crit* value is much less than the calculated *F* value, the variable has significance between the three groups. With the acceptable significance being 0.05 ($p<.05$), the level of significance can be further verified using *F crit* value from 0.01 significance. Calculated *F value* of 16.232716 is less than $F\ crit_{0.01}$ value showing valid significance ($p<.01$).

Table 6.3: ANOVA results for maximum vehicle speed

ANOVA summary of maximum vehicle speed						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.67918981	2	1.83959	0.6778784	0.5107	3.1154
Within Groups	208.959019	77	2.71375			
Total	212.638208	79				

From the Table 6.3, values of *F* and *F crit* can be noted as 0.6778784 and 3.1154 respectively. Since the *F crit* value is larger than the calculated *F* value, the variable has no significance between the three groups. As the other variables like stopping distance and braking distance depend on reaction time to brake, their calculated *F* values show significance. As discussed by Matthew Fowler (Fowler, 2010), the reaction times presented in his thesis were adjusted from what the SSI system measured due to a lag in the reaction time of DBW controllers. There was a lag of 0.5 seconds before the actual servomotor reacted to the acceleration/braking event. In this analysis they were not adjusted as we are only looking at the significance of variables between groups. This statistical quantification gives us information of whether variables like reaction time, stopping distance, etc. had a significant measure towards quantifying the performance of the groups with different controllers.

6.2 Evaluation of Lane Data from Steering Test

The steering evaluation on a mountainous road is very good in testing the characteristics of steering ability and noting accelerating/braking times using the different controllers. Data in the form of lane variation and respective speeds while driving is recorded one point per each 0.2 second. The data is measured by the simulator with some fixed coordinates as shown in Figure 6.1.

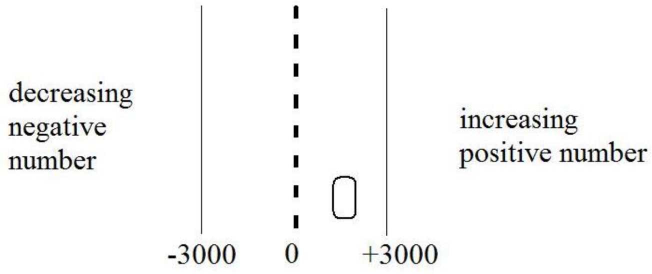


Figure 6.1: Description of lane position inside the simulator system

The vehicle sits in the middle of the road at the defined 1901 position. The width of lane is 3000 units and the value of the lane position vacillates as the vehicle goes out of the lane to its right or left as shown in Figure 6.1. The lane position increases as the vehicle moves to the right and decreases as the vehicle moves to the left. As there is a lot of variation in the lane position values, percent error in lane variation of straight road and curved paths is plotted as shown in the Figure 6.2 and 6.3. The graphs below show a general trend for most of the drivers. Figures 6.2, 6.3, 6.4, 6.5, 6.6, 6.7 shows steering data for users from 18-64 years old, 65+ years old and people with disabilities groups respectively on a straight road and curved path.

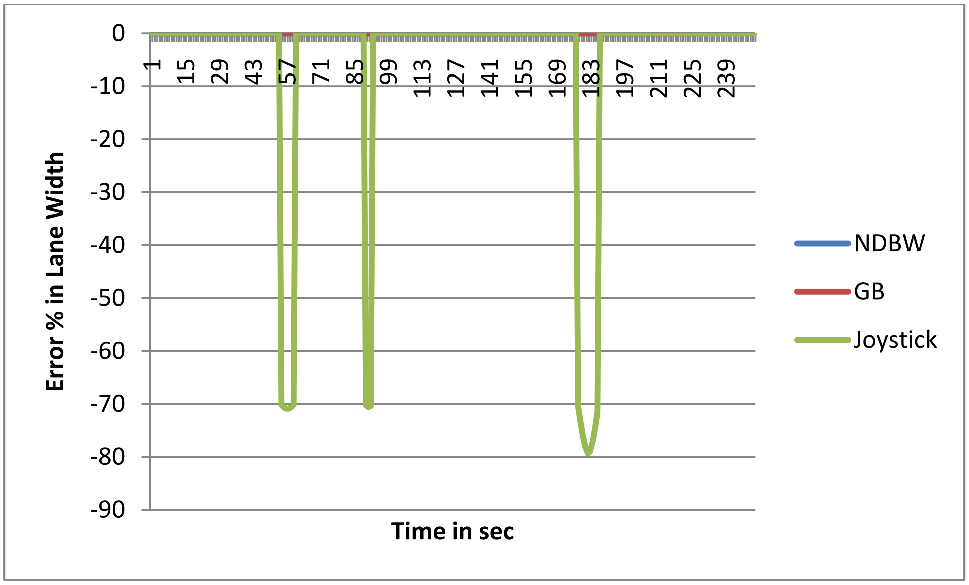


Figure 6.2: Sample straight line steering results for 18-64 group

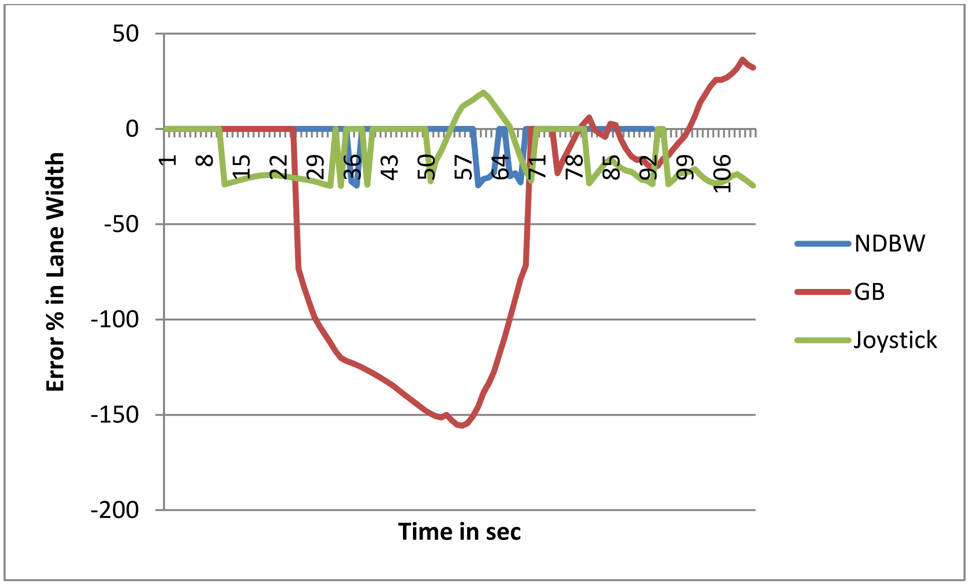


Figure 6.3: Sample curved line steering results for 18-64 group

Percent error of lane variation is calculated as follows for a lane width of 3000 units (Fowler, 2010).

1) If position is between 900 and 2100 units, %error=0

2) If position is greater than 2100 or less than 900, %error = (position-lane width)/lane width*100

From the graphs, different colored lines represent variation of percent error of lane variation through time. The blue line represents NDBW, the red line GB, and the joystick with a green line. From the Figure 6.2, both the NDBW and GB systems were marked with zero variation. The joystick showed a constant deflection from the lane at 57, 90 and 183 time points of 0.2 second each. This shows that the joystick was more variable than the NDBW and GB or in other words it was hard to control the lane position with a joystick on a straight path. In Figure 6.3, the NDBW showed the least variation of all the three controllers with only three missed lane maneuvers. Though the joystick had constant errors throughout, the magnitude of the maximum error was -26% (the sign indicates right side variation, i.e., driving outside of the right side of the lane), whereas the lane variation With the GB controller at curves was greatest among the three controllers with a magnitude of -158% (i.e. more than 1.5 times the width of the lane to its right, where 100% error represents a one full lane width). There was also a constant oscillation along the lane before the error was corrected. Also observing Figures 6.4, 6.5, 6.6, 6.7 similar observations of variability of joystick on straight paths and variability of GB on curved path can be made. From the above observation we can infer two things.

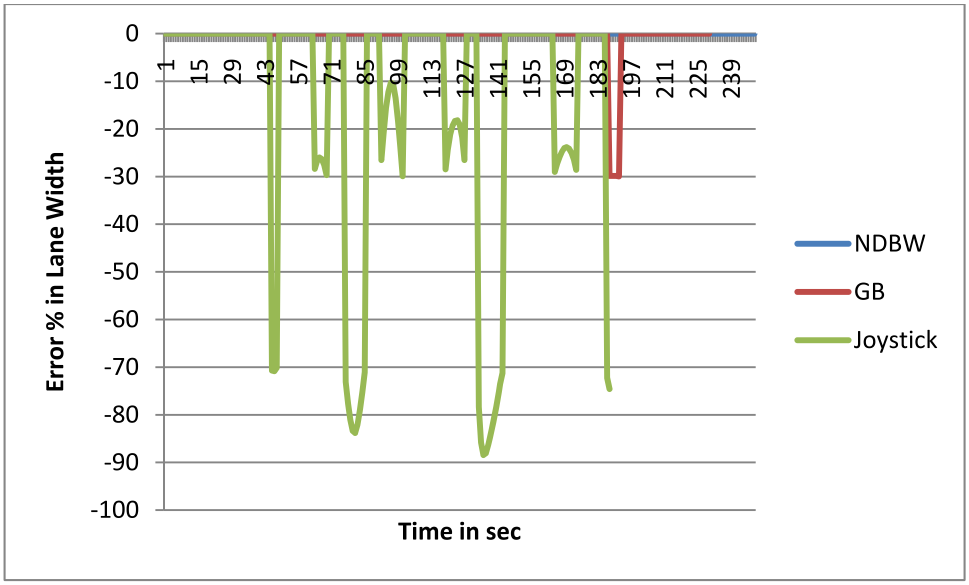


Figure 6.4: Sample straight line steering results for 65+ group

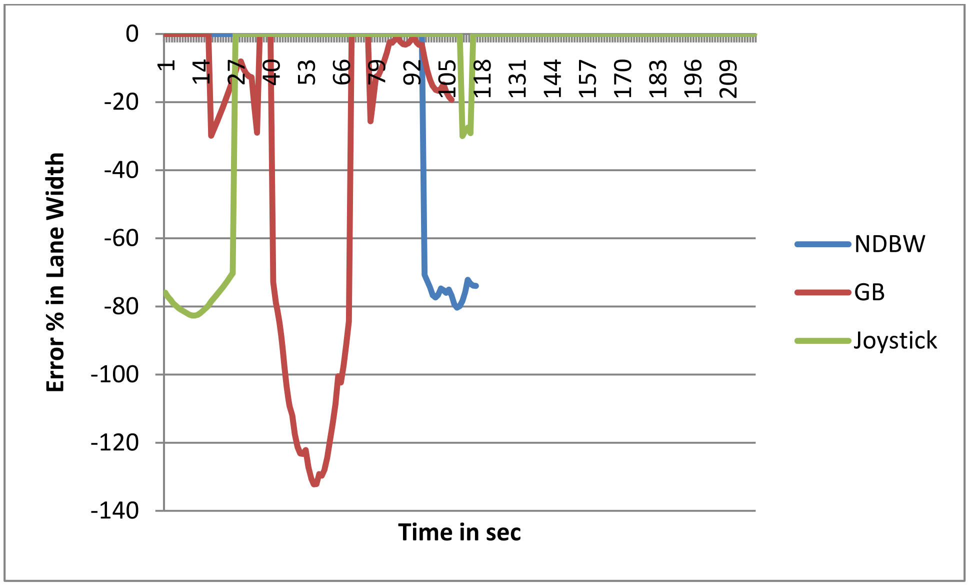


Figure 6.5: Sample curved line steering results for 65+ group

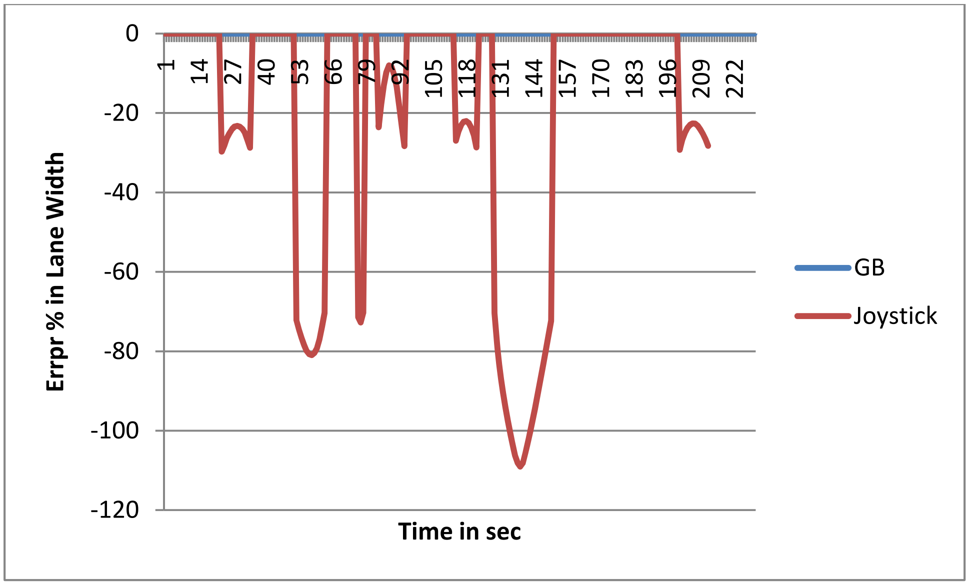


Figure 6.6: Sample straight line steering results for PWD group

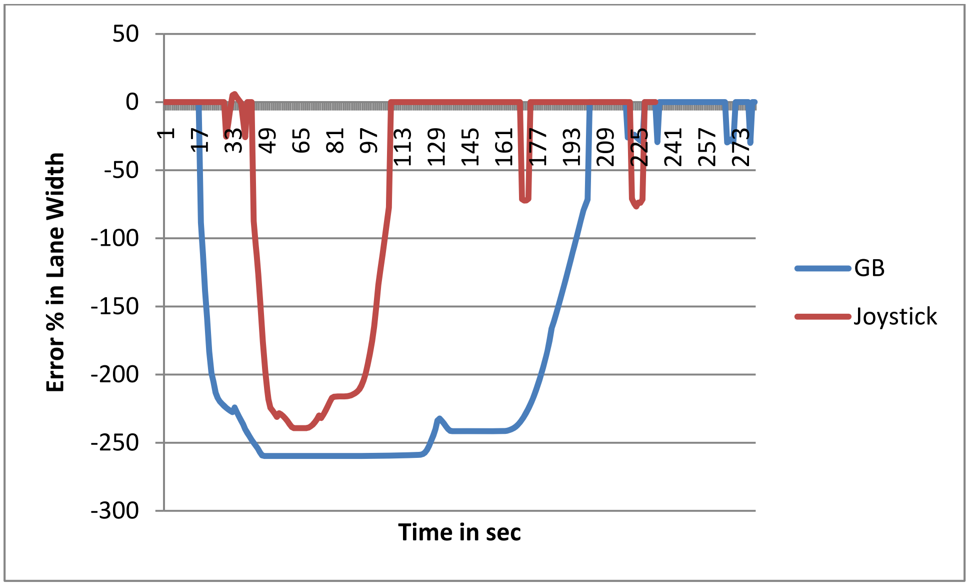


Figure 6.7: Sample curved line steering results for PWD group

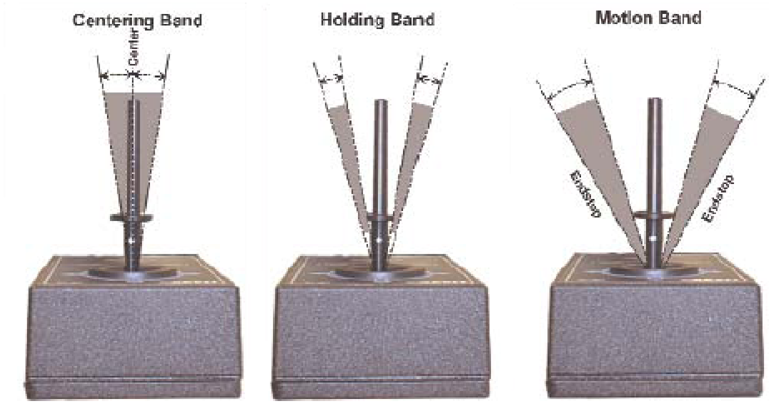


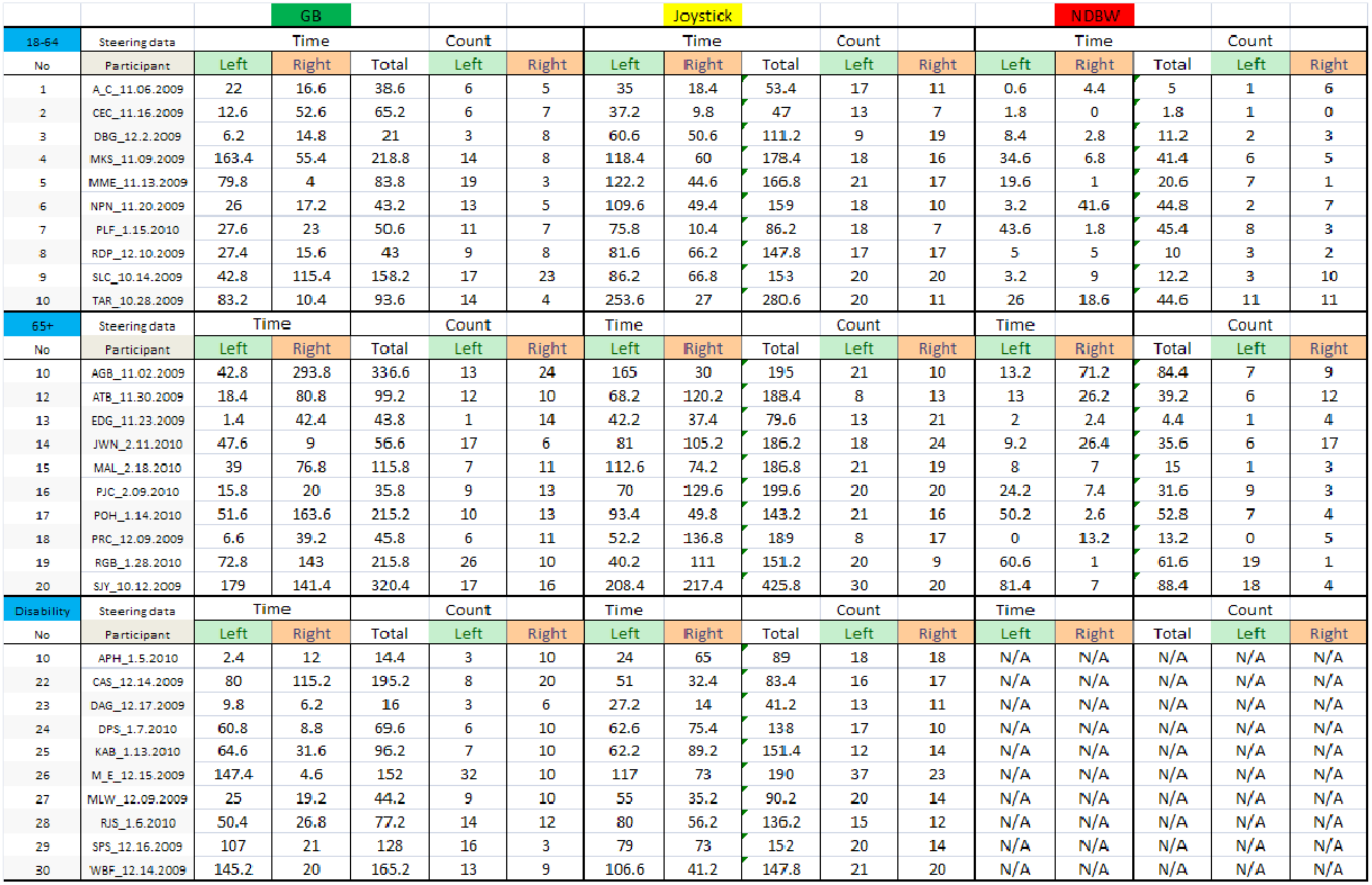
Figure 6.8: Joystick control bands (AEVIT Owners Manual)

First, the functionality of the joystick on straight paths is unpredictable. This is due to the lack of feedback and control in the joystick. There is a voltage band (refer to Figure 6.8) (refer to (Fowler, 2010)) in the joystick which causes a slack in the movement of the joystick even before the actual motor which drives the steering column of the car moves. So the driver tends to over steer when he/she tries to make small adjustments. Second, the curved path maneuvers are tedious with a GB controller. The fact that the reduced effort steering wheel of the GB controller lacks a reversal mechanism to center its steering position causes the driver to over steer to one side. When he/she tries to get back into the lane, lack of perception of the center position leads him/her to travel to the other side. Only after a few corrections in the actual position of the lane is tracked. This observation can be clearly observed from the Figures 6.2 and 6.3.

Using the C++ program, the raw data from the simulator is compiled to obtain the total time spent out of the lane and number of missed maneuvers outside the lane. The simulator records the raw data of specific coordinates of vehicle position in the lane into a text file at a rate of 5 readings per second. This data does not have any units for the vehicle position. This makes it difficult to analyze the raw steering data. After testing the end position of each lane, it is concluded that the width of the car is 1800 units. So observing the Figure 6.1, the lane widths presented are -3000<0<3000. So calculating the end limits of vehicle position, it is calculated as 900-2100 units. Utilizing the conclusions made above, a C++ program is structured in a way that the raw data file is analyzed line by line and number of out of lane maneuvers to left and right side are recorded. Also the total time spent outside the lane is calculated. This synthesized data is recorded into a separate text file, so that it can be accessed and analyzed statistically. It is also important to observe that, the lane widths in the route varied from 2500 to 8000 units. So the program consists of separate subroutines to compute corresponding lane widths. The program is listed in the Appendix C.

The total time spent outside the lane quantifies the performance of different drivers with different controllers. The compiled data is also shown in Table 6.4. Box-plot method is used to represent the data as it gives us the quantitative understanding of the performance of the controllers. From Figure 6.9, the box represents boundaries of the 1st and 3rd quartile. The horizontal bar inside the box represents mean value and small horizontal lines at the top and bottom represents maximum and minimum values respectively. The vertical axis represents the time in seconds.

Table 6.4: Output file for steering data



			GB					Joystick					NDBW			
18-64	Steering data		Time		Count			Time		Count			Time		Count	
No	Participant	Left	Right	Total	Left	Right	Left	Right	Total	Left	Right	Left	Right	Total	Left	Right
1	A_C_11.06.2009	22	16.6	38.6	6	5	35	18.4	53.4	17	11	0.6	4.4	5	1	6
2	CEC_11.16.2009	12.6	52.6	65.2	6	7	37.2	9.8	47	13	7	1.8	0	1.8	1	0
3	DBG_12.2.2009	6.2	14.8	21	3	8	60.6	50.6	111.2	9	19	8.4	2.8	11.2	2	3
4	MKS_11.09.2009	163.4	55.4	218.8	14	8	118.4	60	178.4	18	16	34.6	6.8	41.4	6	5
5	MME_11.13.2009	79.8	4	83.8	19	3	122.2	44.6	166.8	21	17	19.6	1	20.6	7	1
6	NPN_11.20.2009	26	17.2	43.2	13	5	109.6	49.4	159	18	10	3.2	41.6	44.8	2	7
7	PLF_1.15.2010	27.6	23	50.6	11	7	75.8	10.4	86.2	18	7	43.6	1.8	45.4	8	3
8	RDP_12.10.2009	27.4	15.6	43	9	8	81.6	66.2	147.8	17	17	5	5	10	3	2
9	SLC_10.14.2009	42.8	115.4	158.2	17	23	86.2	66.8	153	20	20	3.2	9	12.2	3	10
10	TAR_10.28.2009	83.2	10.4	93.6	14	4	253.6	27	280.6	20	11	26	18.6	44.6	11	11
65+	Steering data	Time			Count		Time			Count		Time			Count	
No	Participant	Left	Right	Total	Left	Right	Left	Right	Total	Left	Right	Left	Right	Total	Left	Right
10	AGB_11.02.2009	42.8	293.8	336.6	13	24	165	30	195	21	10	13.2	71.2	84.4	7	9
12	ATB_11.30.2009	18.4	80.8	99.2	12	10	68.2	120.2	188.4	8	13	13	26.2	39.2	6	12
13	EDG_11.23.2009	1.4	42.4	43.8	1	14	42.2	37.4	79.6	13	21	2	2.4	4.4	1	4
14	JWN_2.11.2010	47.6	9	56.6	17	6	81	105.2	186.2	18	24	9.2	26.4	35.6	6	17
15	MAL_2.18.2010	39	76.8	115.8	7	11	112.6	74.2	186.8	21	19	8	7	15	1	3
16	PJC_2.09.2010	15.8	20	35.8	9	13	70	129.6	199.6	20	20	24.2	7.4	31.6	9	3
17	POH_1.14.2010	51.6	163.6	215.2	10	13	93.4	49.8	143.2	21	16	50.2	2.6	52.8	7	4
18	PRC_12.09.2009	6.6	39.2	45.8	6	11	52.2	136.8	189	8	17	0	13.2	13.2	0	5
19	RGB_1.28.2010	72.8	143	215.8	26	10	40.2	111	151.2	20	9	60.6	1	61.6	19	1
20	SJY_10.12.2009	179	141.4	320.4	17	16	208.4	217.4	425.8	30	20	81.4	7	88.4	18	4
Disability	Steering data	Time			Count		Time			Count		Time			Count	
No	Participant	Left	Right	Total	Left	Right	Left	Right	Total	Left	Right	Left	Right	Total	Left	Right
10	APH_1.5.2010	2.4	12	14.4	3	10	24	65	89	18	18	N/A	N/A	N/A	N/A	N/A
22	CAS_12.14.2009	80	115.2	195.2	8	20	51	32.4	83.4	16	17	N/A	N/A	N/A	N/A	N/A
23	DAG_12.17.2009	9.8	6.2	16	3	6	27.2	14	41.2	13	11	N/A	N/A	N/A	N/A	N/A
24	DPS_1.7.2010	60.8	8.8	69.6	6	10	62.6	75.4	138	17	10	N/A	N/A	N/A	N/A	N/A
25	KAB_1.13.2010	64.6	31.6	96.2	7	10	62.2	89.2	151.4	12	14	N/A	N/A	N/A	N/A	N/A
26	M_E_12.15.2009	147.4	4.6	152	32	10	117	73	190	37	23	N/A	N/A	N/A	N/A	N/A
27	MLW_12.09.2009	25	19.2	44.2	9	10	55	35.2	90.2	20	14	N/A	N/A	N/A	N/A	N/A
28	RJS_1.6.2010	50.4	26.8	77.2	14	12	80	56.2	136.2	15	12	N/A	N/A	N/A	N/A	N/A
29	SPS_12.16.2009	107	21	128	16	3	79	73	152	20	14	N/A	N/A	N/A	N/A	N/A
30	WBF_12.14.2009	145.2	20	165.2	13	9	106.6	41.2	147.8	21	20	N/A	N/A	N/A	N/A	N/A

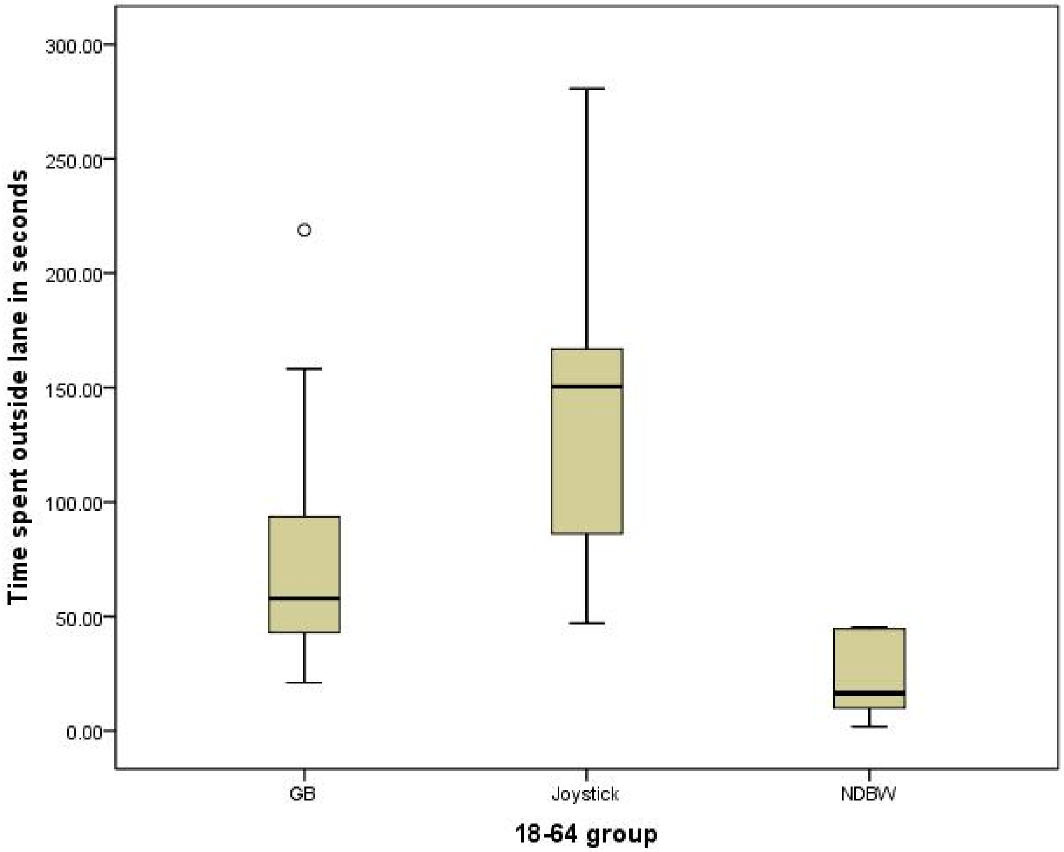


Figure 6.9: Total time spent outside the lane (18-64 group)

From Figure 6.9, we can observe that mean values (or 2nd quartile) of time spent by the 18-64 group outside the lane with the GB, joystick and NDBW controllers are 56 seconds, 151 seconds, and 30 seconds respectively. It can also be observed that most of the participants in this group are in between 40-85 seconds, 70-165 seconds and 25-42 seconds for the GB, joystick and NDBW respectively. The highest and lowest values do not have significance as they are too far away from the means. The circle in the GB group shows that the data point is excluded from the plot as the data point is too high when compared with other data points.

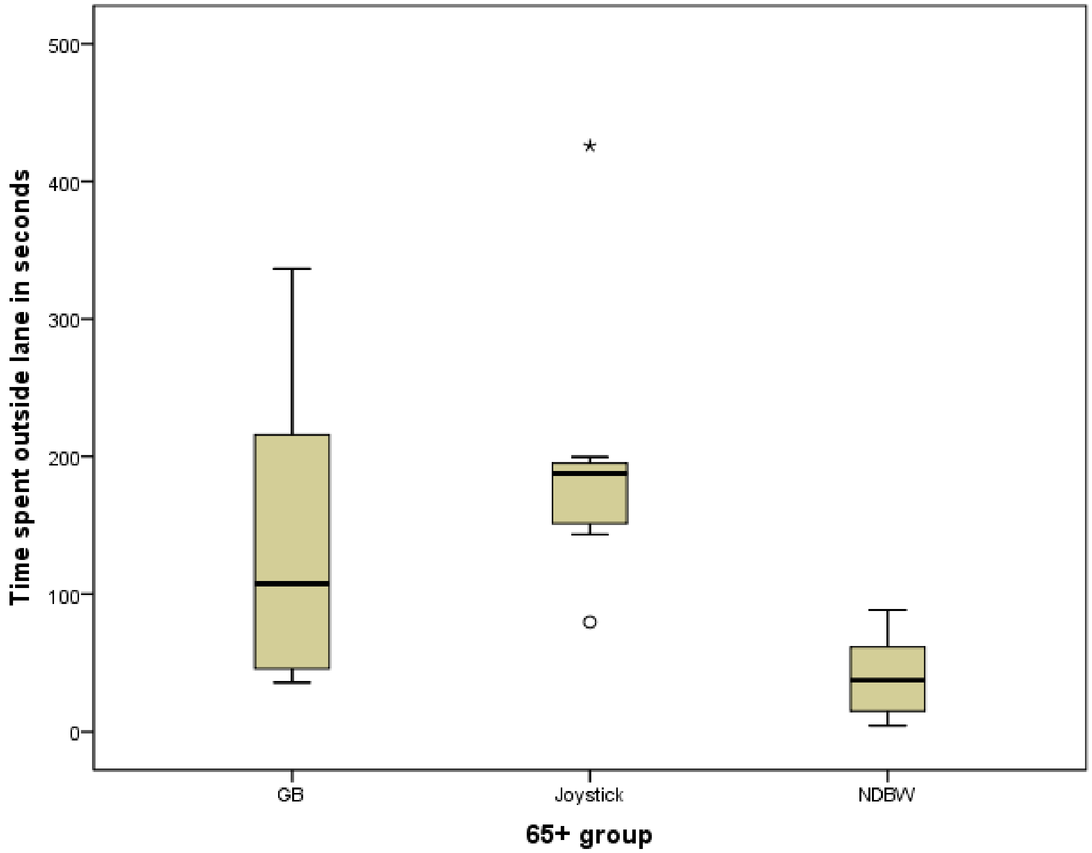


Figure 6.10: Total time spent outside the lane (65+ group)

From Figure 6.10, we can observe that mean values (or 2nd quartile) of time spent by the 65+ group outside the lane with the GB, joystick and NDBW controllers are 107 seconds, 189 seconds, and 50 seconds respectively. It can also be observed that most of the participants in this group are in between 55-220 seconds, 160-205 seconds and 30-70 seconds for the GB, joystick and NDBW respectively. The highest and lowest values do not have significance as they are too far away from means. The circle and asterisk in the joystick group shows that the data point is excluded from the plot as the data point is too high or too low when compared with other data points.

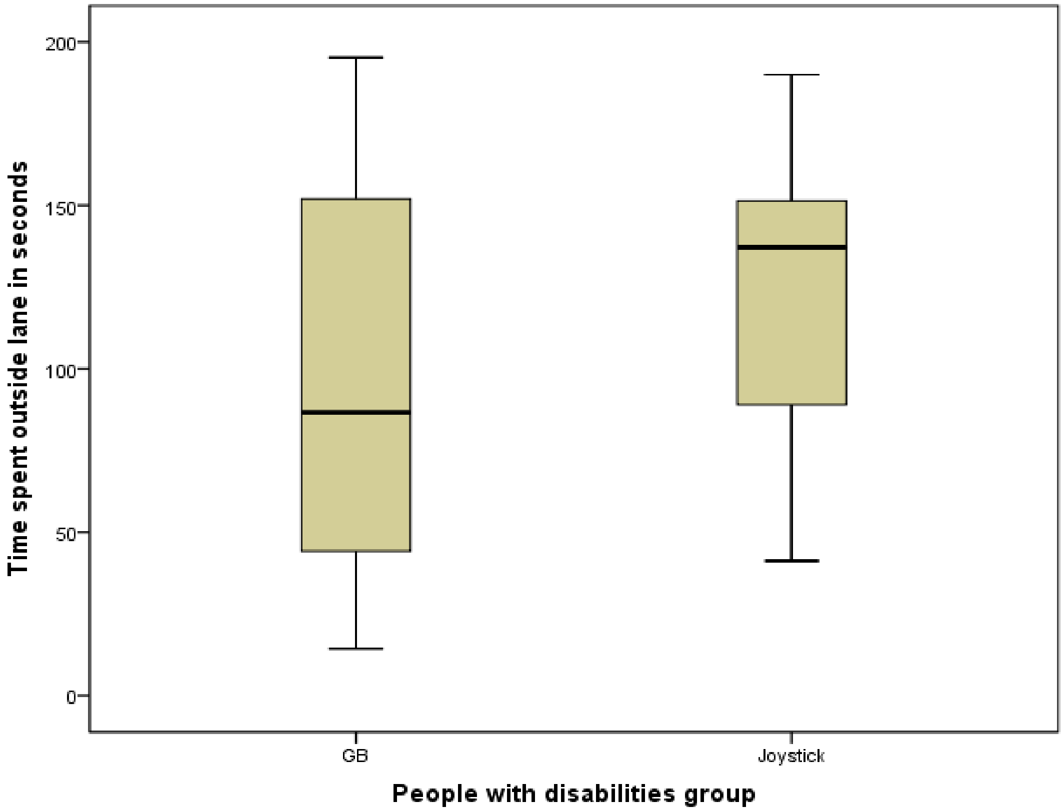


Figure 6.11: Total time spent outside the lane (PWD group)

From Figure 6.11, we can observe that mean values (or 2nd quartile) of time spent by the people with disabilities group outside the lane with GB and joystick controllers are 80 seconds and 136 seconds respectively. It can also be observed that most of the participants in this group are in between 42-155 seconds and 83-158 seconds for the GB and joystick respectively. The highest and lowest values do not have significance as they are too far away from the mean. From a cumulative comparison among the three groups, people with disabilities did better with the DBW controllers. This might be due to their prior use of assistive devices for driving. Comparing the mean values from above graphs, 18-64 group did better with all the three controllers when compared to 65+ group. This might be due to better cognitive capabilities of younger group (less time spent outside the lane means better performance). The following graphs (refer to Figure 6.12, 6.13, 6.14) show the number of improper lane maneuvers by different participants with each controller. The left side figure presents the number of out of lane maneuvers to the left and the right side graph presents the number of out of lane maneuvers to the right.

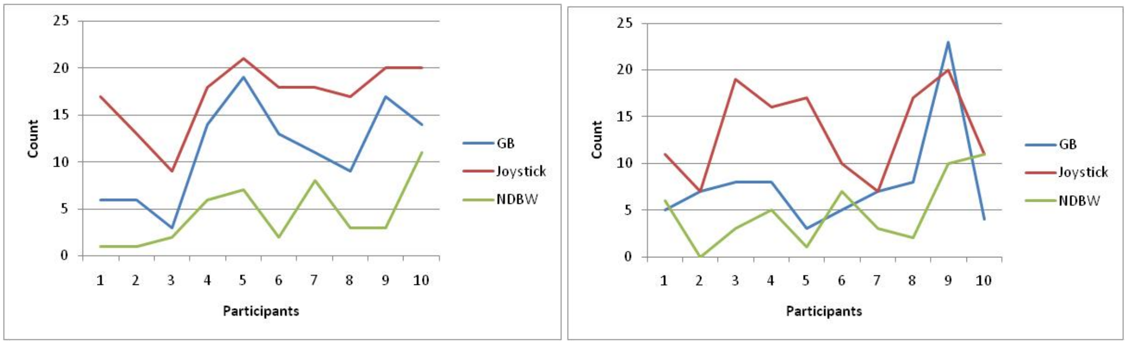


Figure 6.12: Number of left and right out of lane maneuvers, 18-64 group

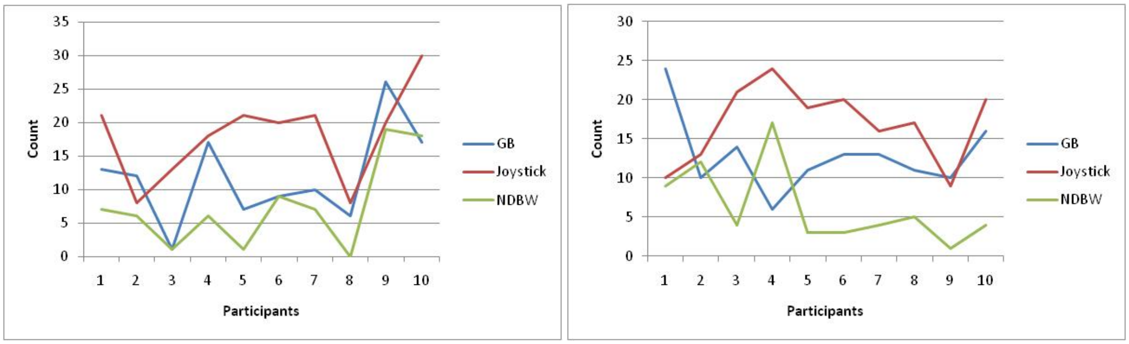


Figure 6.13: Number of left and right out of lane maneuvers, 65+ group

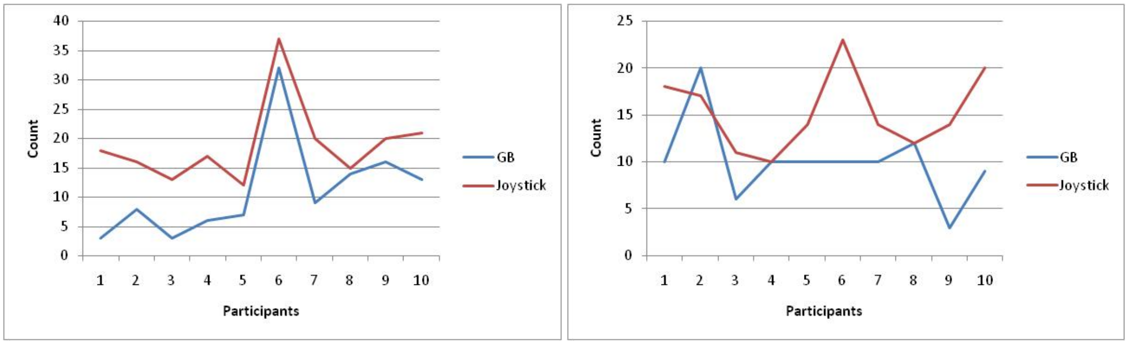


Figure 6.14: Number of left and right out of lane maneuvers, people with disabilities group

From Figure 6.12, the joystick recorded a maximum of 22 from left count and 19 from right count (count here represents the number of times the vehicle went outside the lane). There is a similar pattern in all the graphs. It can be observed from the Figures 6.12, 6.13, 6.14 that the count for the joystick is always highest among the three controllers. The least being NDBW, there are some overlaps between GB and NDBW as seen in Figure 6.12.

6.3 Evaluation of Drivers Ability in Rule Compliance

The rules compliance test is another test where the characteristics of driving with different controllers can be observed. As observed from the testing protocol, the majority of errors made by participants in the city and on the highway came from their inability to maintain lane positions. The joystick controller was the most difficult to maintain the straight lane positions. In this study, statistical analysis using the ANOVA method is used to determine the significance of the specific variables like speed infractions, inadequate space cushions, improper lane position, turn signals missed, and dangerous intersection crossings. Among all the variables, improper lane position showed a significant difference when compared between the groups.

Table 6.5: ANOVA results for improper lane position (Route A)

ANOVA summary for Improper Lane Position - Route A						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	851.5	2	425.7	9.528	2E-04	3.12
Within Groups	3307	74	44.68			
Total	4158	76				

Table 6.6: ANOVA results for improper lane position (Route E)

ANOVA summary for Improper Lane Position - Route E						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2020	2	1010	13.48	1E-05	3.12
Within Groups	5543	74	74.91			
Total	7563	76				

From Table 6.5, the calculated F value is 9.528 and is much higher than 3.12 (*F crit*), which shows that there is significant difference in lane positions between the three groups. Also F value from Table 6.6 is much higher (13.48) than *F crit* value (3.12). This shows that irrespective of the driving condition (i.e. city or highway) there was a significant difference in lane positions among the groups. This signifies that the change in lane positions while driving with different controller is pertinent between the groups. This signifies the quantitative differentiation of driving capabilities between the groups. Further level of significance can be verified by comparing calculated F value (9.528) with $F\ crit_{0.01}$ (4.892). Since the F value is larger than $F\ crit_{0.01}$, there is significance to higher precision. Other variables like speed infractions, inadequate space cushions, missed turn signals, and dangerous intersection crossings did not show any significant change between groups and the tables of analysis of variance are shown in Appendix B (refer to Table B.1).

6.4 Comparison of Driving Performance from Protocol Survey

As discussed earlier, when designed with proper care these performance surveys can help us to understand the performance of driving systems effectively. They form a bridge between the researcher and the user, thus facilitating a better understanding of the human factors involved in driving with the controllers. Our interest being the development of a better interface for driving controllers, we should compare the derived results from section 6.2 to the comments noted by the users. The majority of the comments from the users were as follows.

1) Driving with the joystick on straight roads is tedious, i.e. it is hard to control the straight lane positions with the joystick.
2) Driving with the GB controller is relatively easy, but has over steering tendency when maneuvering curved paths.

To improve the human interface, the controller response to the users at different aspects of driving should be included. The primary driving controls of ability to steer and accelerate/brake should be studied with respect to human limitations and responses.

Table 6.7: Table showing some responses from participants

Hypothesis	Questionnaire responses
A	1.) Please describe your (negative and positive) experiences with the joystick system. Negative- I cannot make minor adjustments to the steering motion. Positive- It is a very good system for making sharp turns. 2.) Please describe your (negative and positive) experiences with joystick system. • To make fine movements on steering was hard. It was in a zigzag movement • This system was easier to make bigger turns compared to GB 3) Please describe your (negative and positive) experiences with joystick system. Negative – It is hard to keep it straight, I cannot feel the controller. Positive – Braking and acceleration is easy.
B	1.) Please describe your (negative and positive) experiences with GB system. • Challenging. It is different from joystick controller. Making steering maneuver to right is difficult, sensitivity is an issue. 2.) Are there any functions that can be added to GB system to assist your use of it (e.g., sudden release button for brake.)? • A feature to assist the driver to center the controller and to create a feel even without looking at it. 3.) Please describe your (negative and positive) experiences GB system. • Steering- It goes really fast to a side. It is more sensitive.
C	1.) Was it easy to navigate/operate this system? Please describe your experience. • It was little bit difficult. Can overcome with training. 2.) Was it easy to navigate/operate GB system? Please describe your experience. • Fairly easy, but need to practice reaction time. 3.) Was it easy to navigate/operate joystick system? Please describe your experience. • Don't have the analog so little bit more learning curve. Steering needs a lot to get used to

From Table 6.7, row ‘A’ shows that driving with the joystick on straight roads is tedious or in other words it is hard to control the straight lane positions with the joystick when compared to curved path maneuvers. Also row ‘B’ shows that driving with the GB controller is relatively easy and has over steering tendency when maneuvering curved paths. Additionally, row ‘C’ gives some background to assist in designing a driver training course

Table 6.7 presents some of the survey responses listed by the user with respect to the GB and joystick controllers. From Table 6.7 section A, we can observe that participants expressed their driving experience with the joystick controller. Ability to make bigger turns efficiently, difficulty in maintaining lane positions, and inability to make small adjustments to one’s lane position are some of the responses expressed by different users. From Table 6.7 section B, participants’ review of the GB controller can be observed. Difficulty making turns and a suggestion to incorporate a reversal mechanism for steering in GB can help us to build the new prototype. Due to the lack of ability to center the steering wheel, participants were over steering to make a turn.

As there is no suggestive way to design a driver training course using the quantitative data from simulator, qualitative data from surveys form a foundation to present the most effective training course for present or future DBW control users. Section C from Table 6.7 presents the need for a driver training course which is discussed in more detail in Section 7.2.

Chapter 7: Conclusion

7.1 Human Factor Characterization for Developing a New Drive-by-Wire Interface

The conclusion to this project would be incomplete without explicitly answering the summary questions presented in chapter 1.

1) What are the differences in performance among different driving systems?

From the results in the previous section, we are left to conclude that the AEVIT joystick is a more difficult to steer than the GB. The NDBW (conventional) system, however, greatly outperformed both the DBW systems with better steering capabilities. On average younger drivers (18-64) spent almost twice the time outside the lane with the GB and five times the time outside the lane with the joystick as compared with the conventional system. Furthermore, older drivers (65+) spent over twice as much time outside the lane with the GB and almost four times the time outside the lane with the joystick as compared with the conventional system. Also the results from one-way Analysis of Variance (ANOVA) showed that certain variables like improper lane position, reaction time to brake, stopping distance, and braking distance showed a significant difference between the groups. This signifies the quantitative differentiation of driving capabilities between the groups. Variables like maximum speed, improper space cushion, and missed turn signals did not show any significant difference between groups.

While the conventional system was shown to be the best option to drive based on the tests for performance, individuals with disabilities are not able to use such a setup and must rely on DBW technology. We have studied DBW systems in hopes of optimizing the performance of the GB and joystick systems to make them practical and safe for individuals with disabilities.

2) Is there a difference in safe driving practices using DBW controls versus standard driving equipment?

While most users enjoyed the separation of the steering and gas/brake, a few found it difficult to coordinate the two successfully. Fortunately most participants noted an improvement in their abilities after repeated use of the system even though they were not given practice. Users also expressed their desire for an armrest for the steering part of the GB (the mini wheel) and the placement of the turn signal on hand controls so that it is more easily accessible. In the present setup, to engage the signal, a user must choose to temporarily let go of either the mini steering wheel or gas/brake mechanism. Obviously this is unsafe, and the design would need to be updated to be used in a vehicle. As discussed in chapter 3, though there is a need to improve the system, the results showed consistency in all trials and in between the participants.

3) How do users perceive the use of the adaptive driving system?

Overall, participants liked the joystick the least of all three systems, primarily due to their difficulty in controlling the vehicle. A few users noted that controlling an entire vehicle with one hand was an intriguing concept, but would wait until the design was improved to install it. While almost all users had difficulty at first, most users' (especially younger ones) abilities improved with use. As with the GB, users expressed interest in an armrest for the joystick. Users also wished for a larger joystick, feeling the current one was too small to be held in the palm. It was difficult for people with disabilities to hold without a gripping fixture like Velcro tape.

4) What are the human factors affecting the control of a vehicle equipped with adaptive driving equipment?

While the data shows that the GB setup outperformed the joystick, it must be noted that the joystick vastly outperformed the GB on curved roads. From section 6.2 we can observe that percent error in lane variation at curves with GB was -158% (i.e. more than 1.5 times the lane width) where joystick had only -28% error deflections from lane at curves. The GB lacks a reversal mechanism to make the miniature steering wheel return to its original position by itself when moved away from that position. This made it difficult for users to ease in and out of turns and led to over steering. Users, however, were usually able to correct their mistakes after a few oscillations out of the lane.

When it came to straight roads, participants found it much easier to stay in the correct lane with the GB, compared to the joystick. The least reliable of the systems, the joystick caused difficulties especially on straight roads. From section 6.2, Figure 6.2 we can observe that three peaks at different levels showing a deviation of -70, -71, -80 % lane variations with the joystick whereas there was no change in percent error with GB and NDBW on straight paths. The device is setup with a movement threshold which must be broken before the system responds (refer to chapter 6 for details about different bands in a joystick). The bands in the joystick are not differentiated properly, making it difficult for participants to stay within the lane on highways (straight roads at high speeds). Furthermore the joystick's movement corresponds to an angular velocity of the wheels as opposed to a position, i.e. holding the joystick at a constant distance from its origin (center) will cause the steering column in the vehicle to turn with a constant speed, not to a defined position (refer to chapter 6 for details about different bands in a joystick). This fact was not evident to most of the users who assumed the system would behave like a normal vehicle. Coupled with the small lag present, participants found it exceedingly difficult to maintain lane position on straight roads. They tended to drift slightly out of the lane and over steer to get back into the lane, often leading to crashes and spin outs. Most users, however, found success on curved roads. The joystick, unlike the GB, returns itself to its origin when released, greatly aiding drivers on turns.

The human factor information gathered in this study leads us to development of new ergonomic DBW user interface which will be discussed in detail in chapter 8.

7.2 Driver Training Program

Though an exact model cannot be proposed based on the results from the study, it is possible to predict a suitable driver training program. It is observed from Analysis of Variance that there is a significant difference between the three groups in various aspects like reaction time, improper lane position etc. Based on the results from section 6.2 and interviews with vendors, it is noted that out of three controllers, the joystick requires more time to train an individual followed by a GB system. A training model is presented in Table 7.1.

Table 7.1: Proposed driver training schedule

s.no	group	controller	Training time		
			steering	reaction time	rules compliance
1	18-64 years	GB	15 min	2	10 min in city
		Joystick	25 min	5	10 min in highway
		NDBW	n/a	n/a	n/a
2	65+ years	GB	20 min	3 or 4	15-20 min in city
		Joystick	25 min	5	15 min in highway
		NDBW	n/a	n/a	n/a
3	PWD	GB	15 min	2	10 min in city
		Joystick	20 min	5	10 min in highway
		NDBW	n/a	n/a	n/a

In Table 7.1, column labeled “reaction time” represents the number of times a driver should repeat the acceleration/brake test. The column “rule compliance” shows minimum practice time in either city or highway depending on the controller. The selection of route for training is done based on the steering data from section 6.2. It is proposed that the time shown above is comfortable to get trained in one day and the driver needs to practice until he/she gets acquainted with the controller. The training should last until the driver gets proficient with controller. He/she should also follow the current driver training program and get qualified by a rehabilitation trainer.

Chapter 8: Future Work

8.1 Designing a Test to Study Human Interactive DBW Prototype

The current project is a pilot study which lays a foundation to the more human centric evaluation of present hand controls to help design a new DBW controller. In this future study, specific scenarios like performance while driving in a tunnel and driving with constant speed along winding roads will provide better ergonomic DBW controls. After characterizing the results from this study, subsequent work focuses on developing a design for a next generation Drive-by-Wire (DBW) vehicle control. The project should be divided into two parts, the human-machine interface and the vehicle electronic control. The first part of this project involves an in-depth study of human factors to develop an interface that ensures an acceptable level of human performance while driving a vehicle. This can be achieved by designing test scenarios which concentrate in depth on the hypothesis proposed in this thesis. For example, to better understand the functionality of the GB controller at curved maneuvers specific tests should target the characteristics of the controller mentioned in section 6.2. The second part of this project will focus on the investigation of a new method for electronically controlling the vehicle. Current vehicle modifications are costly, time intensive to install, and are typically mechanically linked to the existing steering column. For example, a less costly and more efficient operation of

DBW control is to plug directly into the vehicle's assisted steering computer. In this way the device can be a self contained, portable, plug-n-play device.

The objective of the proposed study is to setup a test procedure that involves questionnaires and driving on a simulator in special conditions to evaluate the driver's performance and physical condition using the improved prototype. The goals of the future project are to explore different and adaptive user interfaces, interface placement, and vary functional aspects of current DBW controls. Specifically, user interfaces to be tested are different shapes created for addition to the base stick on the joystick controller or steering wheel, such as a "T," sphere and palm cuffs (refer to Figure 8.1).

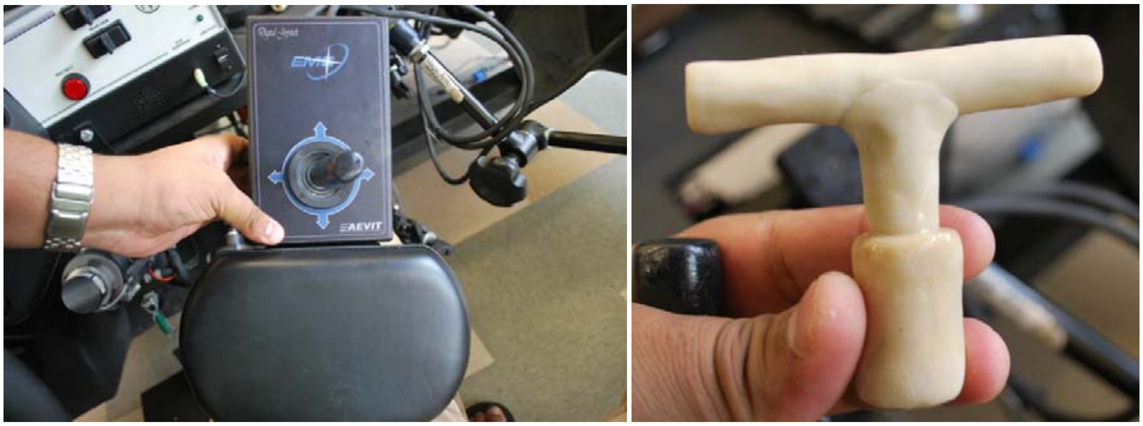


Figure 8.1: A palm rest and add-on to joystick

Customer centric ergonomic fixtures often exist in the modified vans but it is unknown whether they actually help the user. In this study performance evaluation is done using the already existing fixtures and new fixtures to better the ergonomics of the hand controls. They are validated by testing their performance. In this future study, measuring quantitative data of human physical condition is given importance. Driver ability to perform a task is directly related to the user stress (i.e. his heart rate). In order to perform a task well, the heart rate of the user increases (Lenneman & Backs, 2009). So the aforementioned tests for controller ergonomics can be evaluated according to the Heart Rate Variability (HRV) from a non invasive cardiac measuring instrument. Figure 8.2 shows a flowchart explaining the details of the proposed tests.

Figure 8.2: Process flow chart

Test scenarios such as driving through a tunnel and driving on a country road while maintaining a constant speed and lane position are some of the tests suggested for the future study.

8.2 Development of New Drive-by-Wire Prototype

The next generation DBW system is expected to have better functionality in steering and ability to sense the vehicular movements. To achieve this, the future DBW system should possibly include a locking mechanism like a ratchet and pin mechanism to mechanically sense the movement of the controller. The future attachment is expected to elicit the feel of the controller so that the user can actually sense the position of the joystick even without looking at it. The second modification pertains to the GB controller. To facilitate self-centering of the steering wheel (i.e. allowing the miniature steering wheel to center itself or assist the user to properly center the steering wheel), a swirl spring is attached to the reduced effort steering wheel in the GB controller. This attachment helps the users to auto center the steering wheel, enabling them to make better curved maneuvers. Though these attachments might help better the design, more human centric analysis should be done as a future work prior to incorporating all the modifications.

8.3 Analysis of Data

As discussed earlier in section 6.1, there is further need for analysis of the driving data. Additional comparisons using two-way ANOVA can be helpful to determine relations within groups and between groups. A Post Hoc test can be conducted for a more detailed analysis of one-to-one group comparisons. Tukey test is a pre dominant suggestion for the comparison of data. These analyses help in characterizing a future driver training program. Though a proposal for a driver training program is presented in this paper, it is derived from qualitative results from surveys. These analyses help to determine a driver course quantitatively using data collected from simulator. Furthermore, driver safety information collected from rules compliance test can be analyzed using a regression analysis by comparing different variables including rules compliance ability, ability to use turn signals etc. with respect to age. This analysis will give us information about human limitations and behaviors while driving with the controllers. Lane data can be analyzed using standard deviation tests to determine the functionality of each controller.

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Appendices

Appendix A: Graphs for the Steering Data

The following figures show the straight and curved path steering results for each participant. The % error outside the lane with respect to time is graphed (-% indicates right side and +% indicate left side).

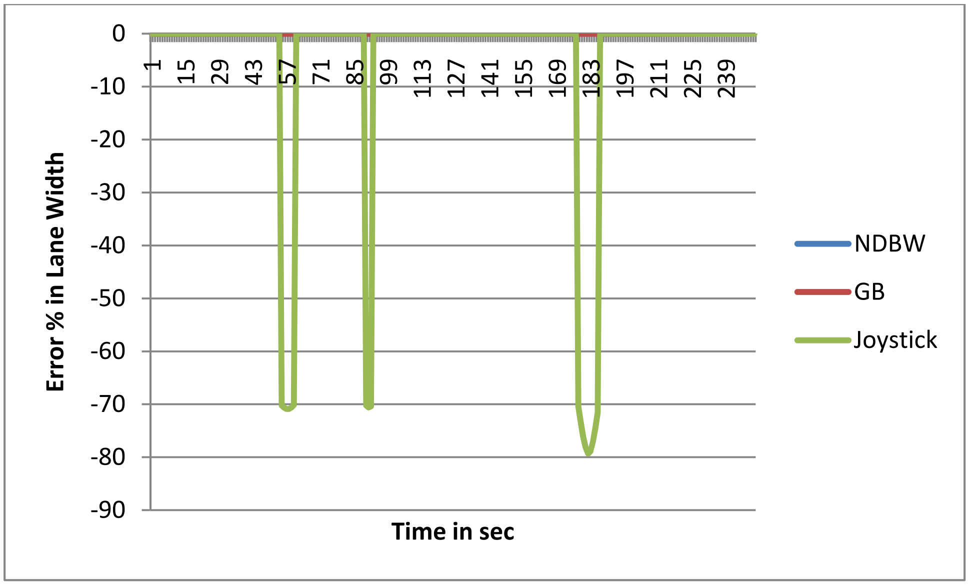


Figure A.1: Straight line steering results, Group I: participant 1

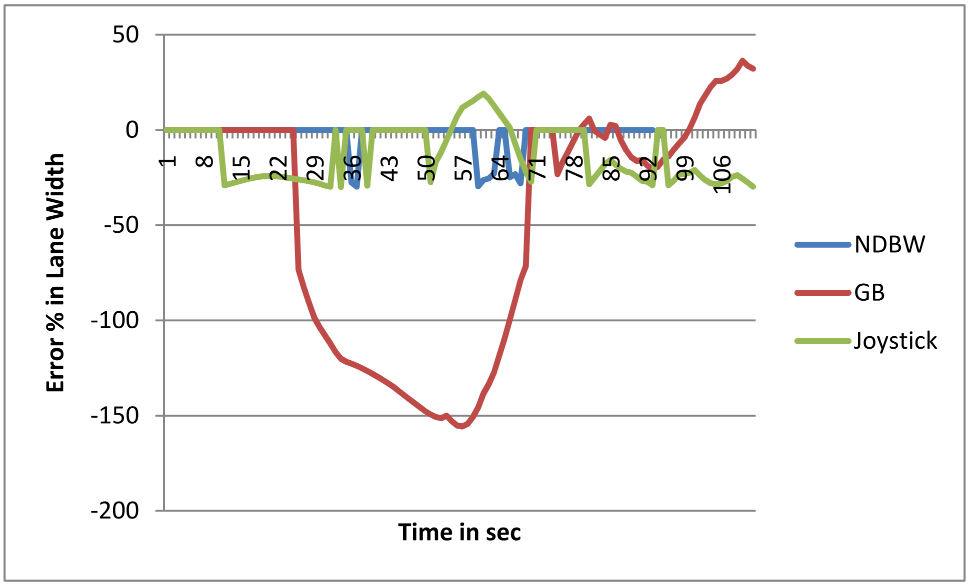


Figure A.2: Curved line steering results, Group I: participant 1

Appendix A: (Continued)

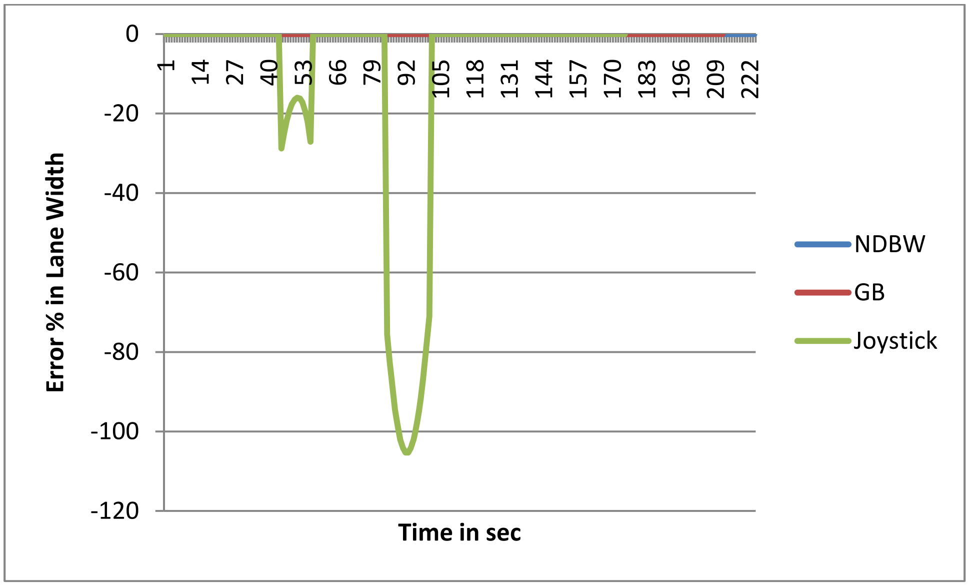


Figure A.3: Straight line steering results, Group I: participant 2

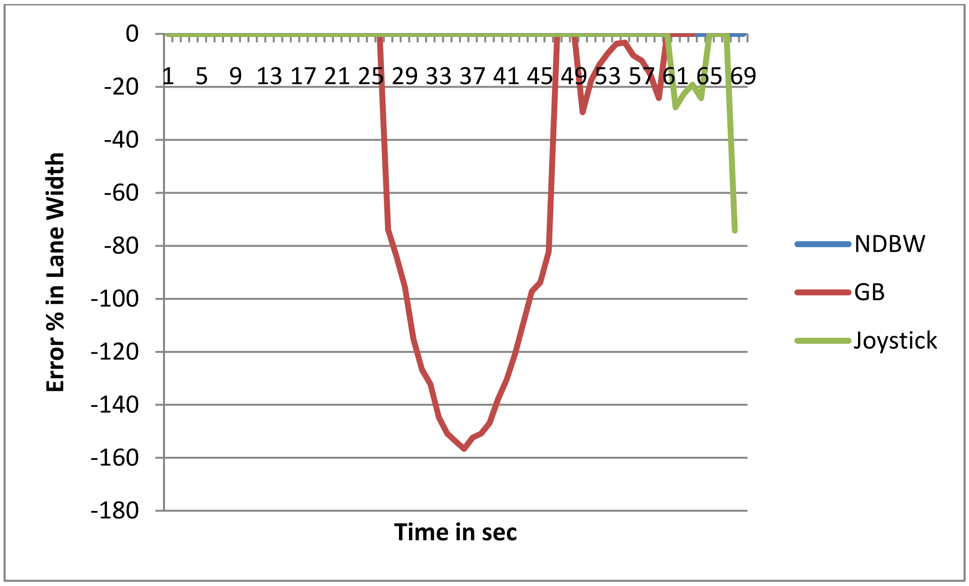


Figure A.4: Curved line steering results, Group I: participant 2

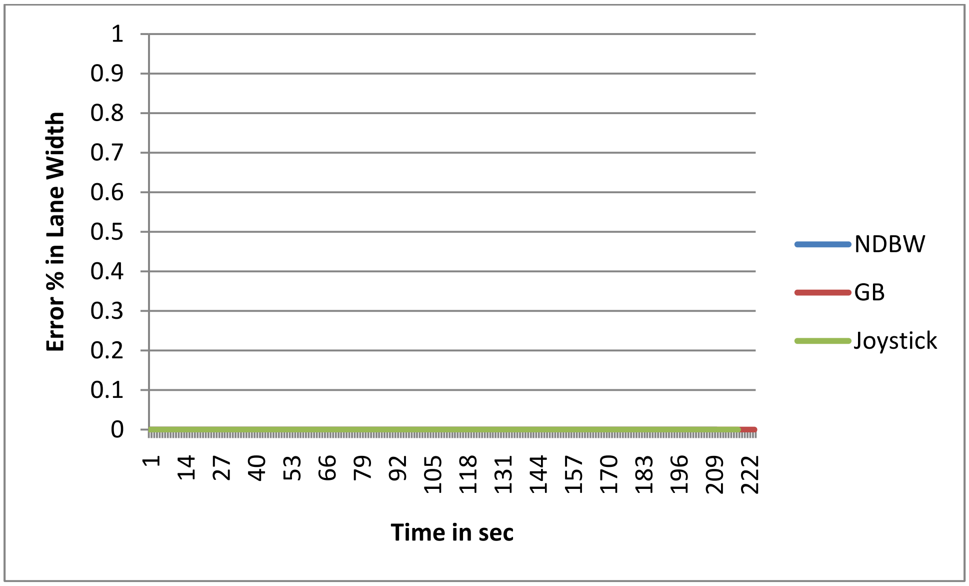


Figure A.5: Straight line steering results, Group I: participant 3

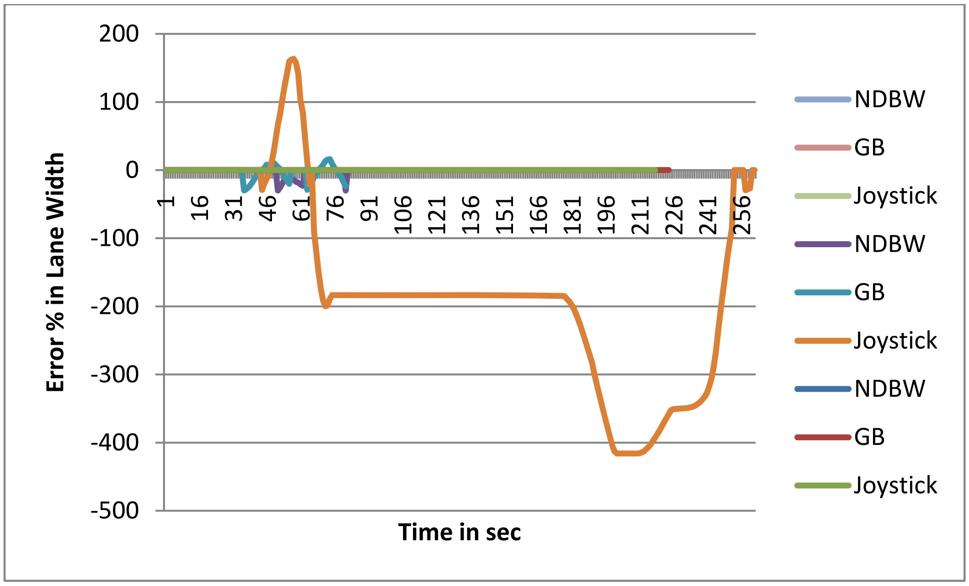


Figure A.6: Curved line steering results, Group I: participant 3

Appendix A: (Continued)

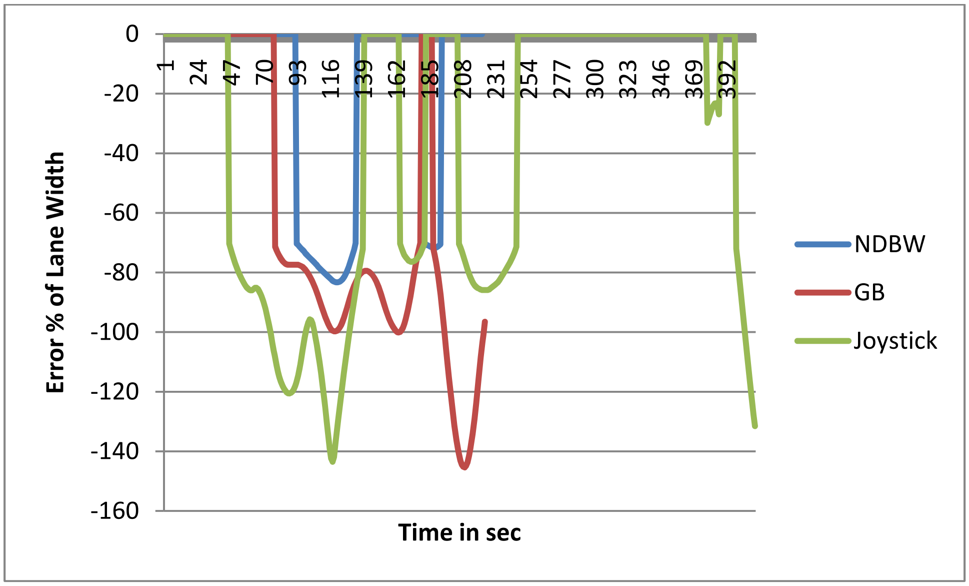


Figure A.7: Straight line steering results, Group I: participant 4

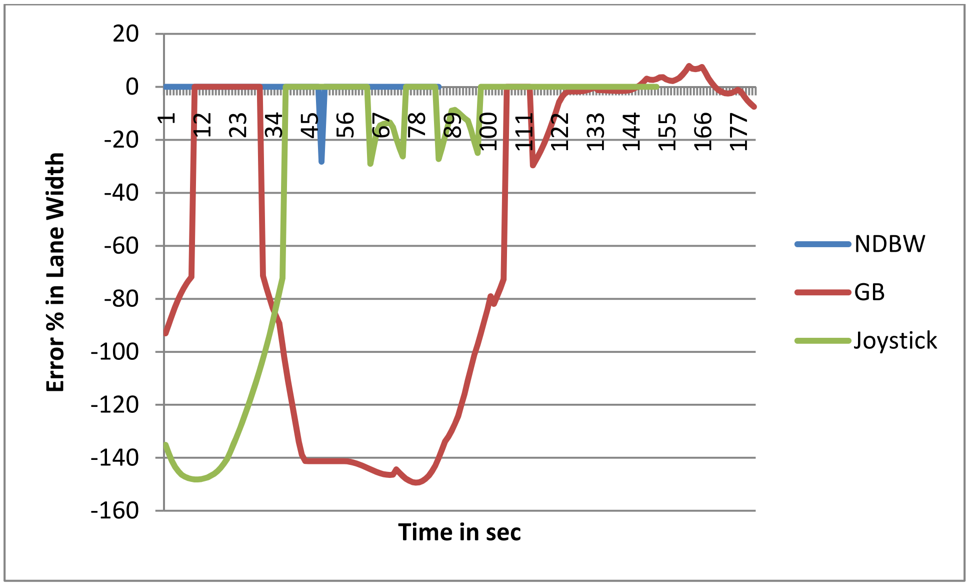


Figure A.8: Curved line steering results, Group I: participant 4

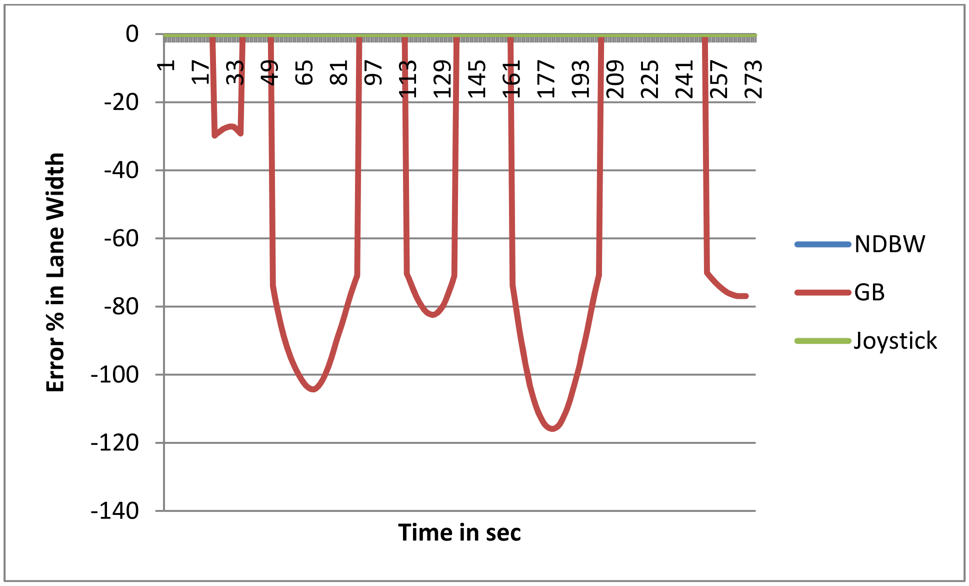


Figure A.9: Straight line steering results, Group I: participant 5

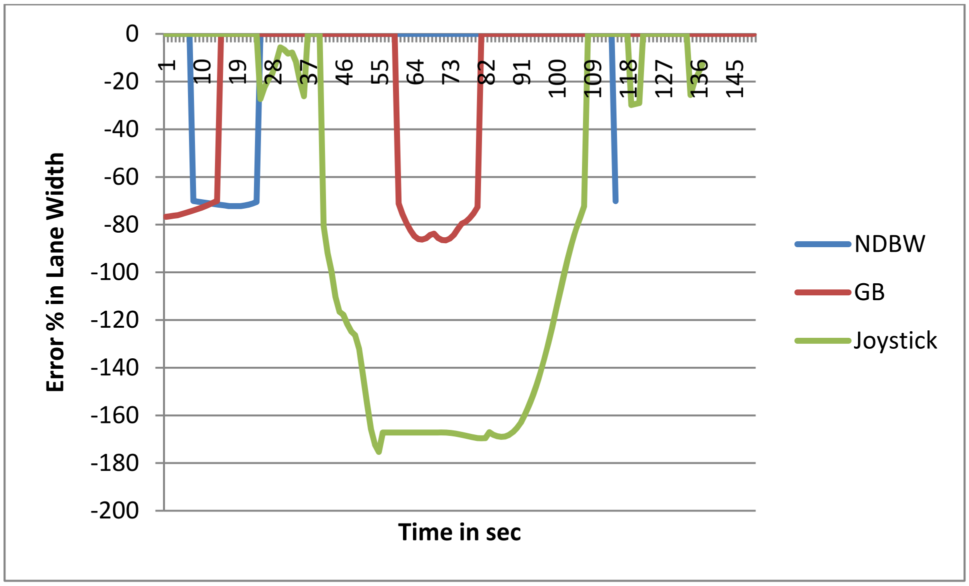


Figure A.10: Curved line steering results, Group I: participant 5

Appendix A: (Continued)

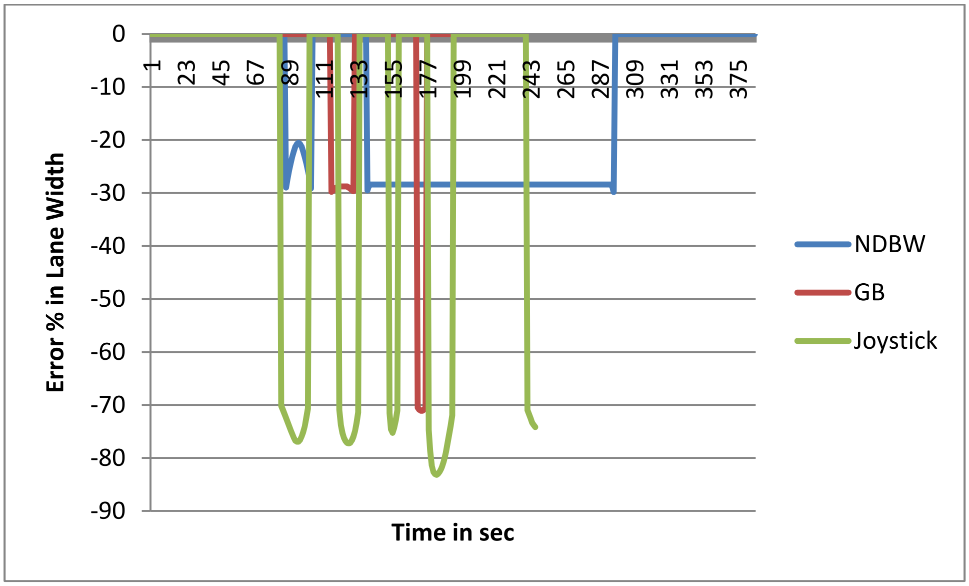


Figure A.11: Straight line steering results, Group I: participant 6

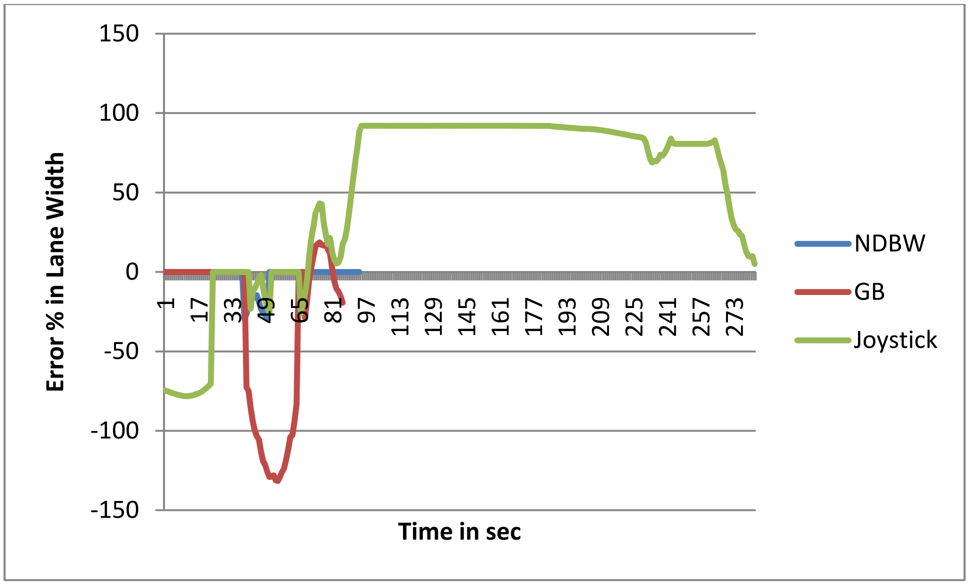


Figure A.12: Curved line steering results, Group I: participant 6

Appendix A: (Continued)

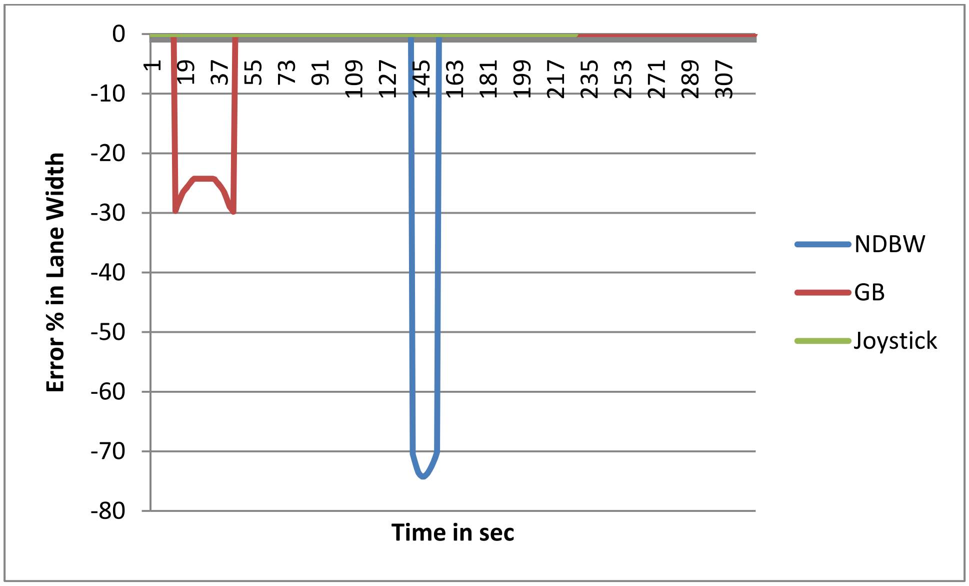


Figure A.13: Straight line steering results, Group I: participant 7

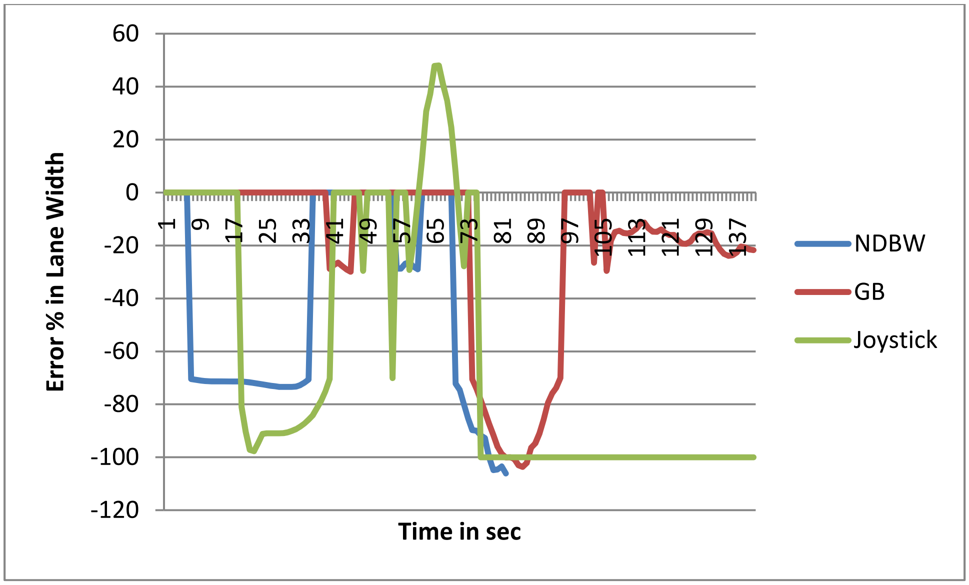


Figure A.14: Curved line steering results, Group I: participant 7

Appendix A: (Continued)

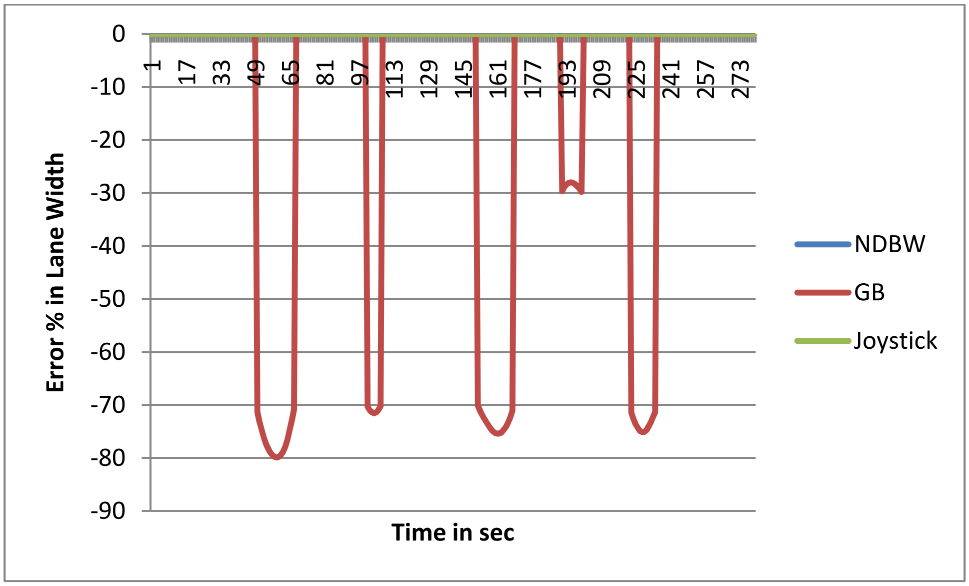


Figure A.15: Straight line steering results, Group I: participant 8

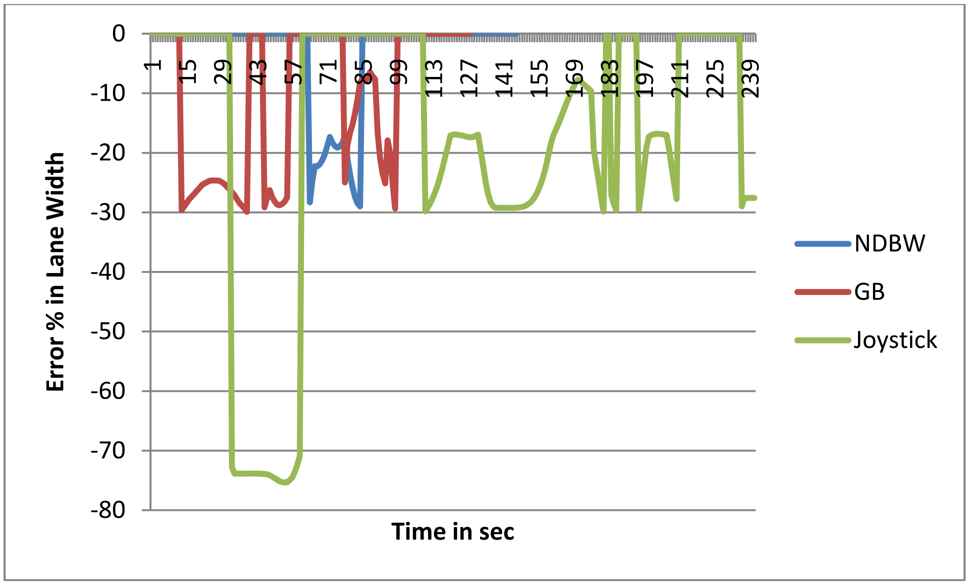


Figure A.16: Curved line steering results, Group I: participant 8

Appendix A: (Continued)

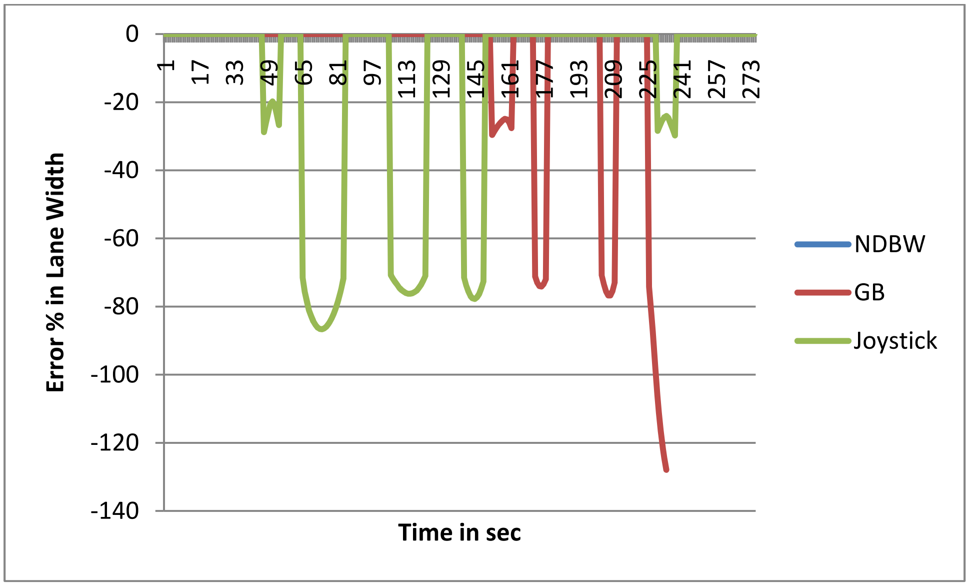


Figure A.17: Straight line steering results, Group I: participant 9

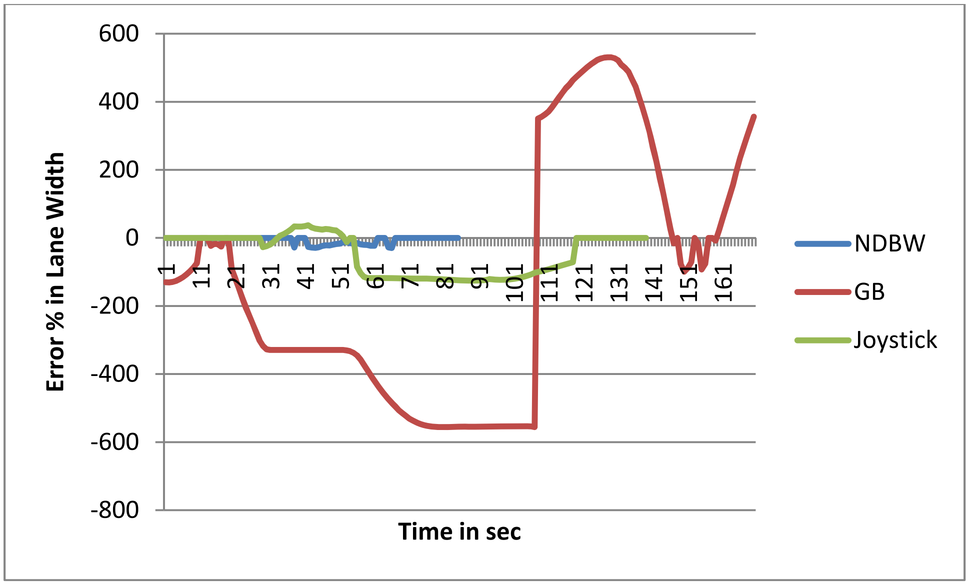


Figure A.18: Curved line steering results, Group I: participant 9

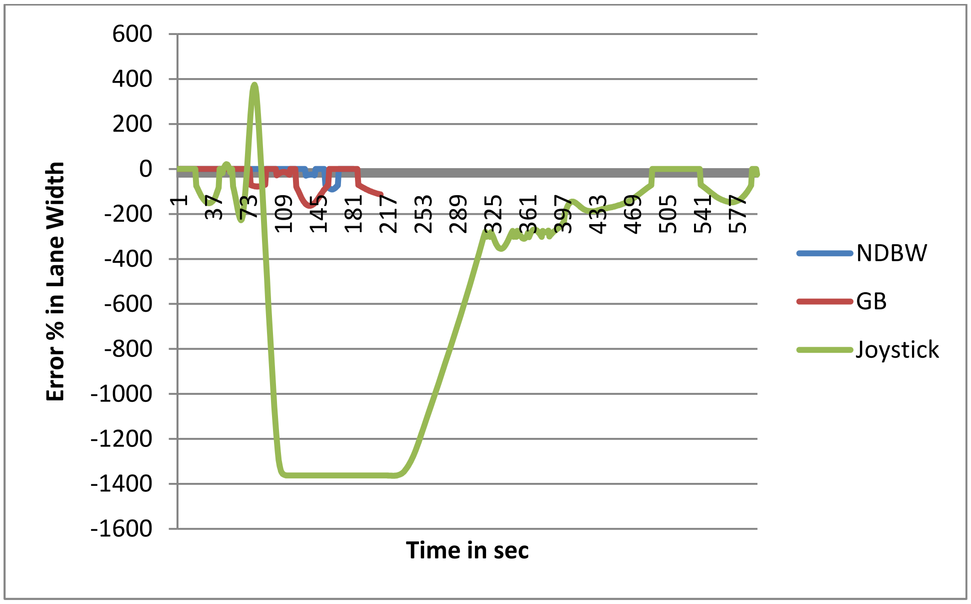


Figure A.19: Straight line steering results, Group I: participant 10

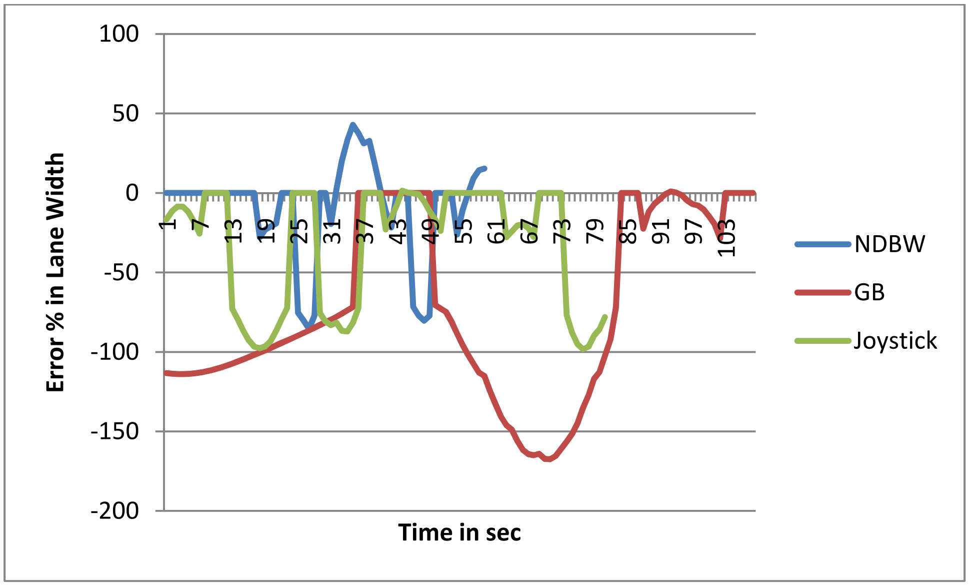


Figure A.20: Curved line steering results, Group I: participant 10

Appendix A: (Continued)

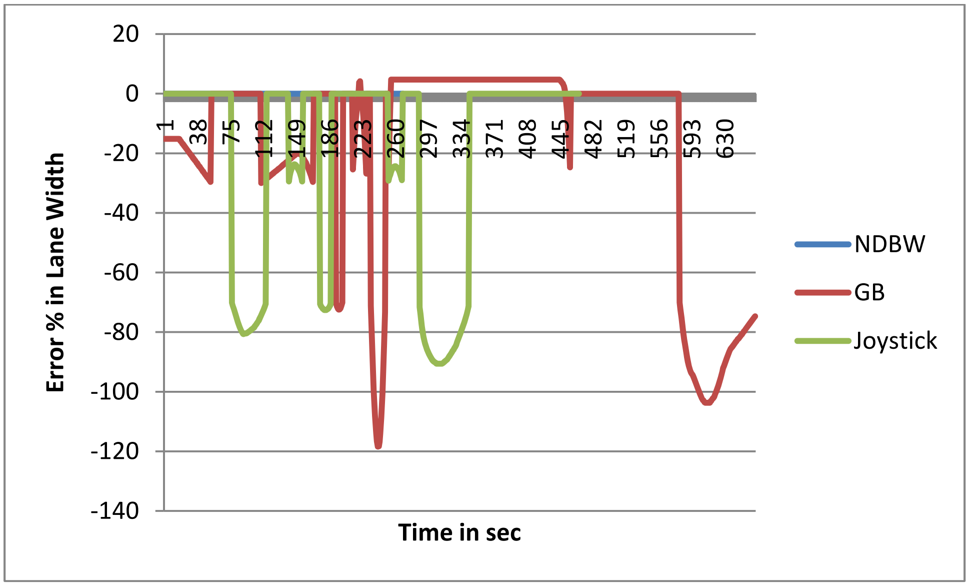


Figure A.21: Straight line steering results, Group II: participant 1

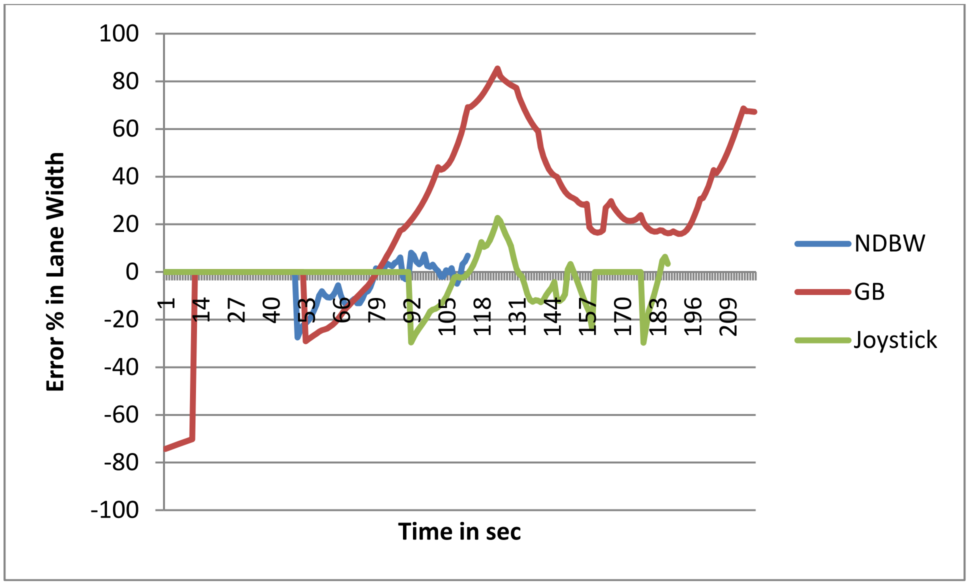


Figure A.22: Curved line steering results, Group II: participant 1

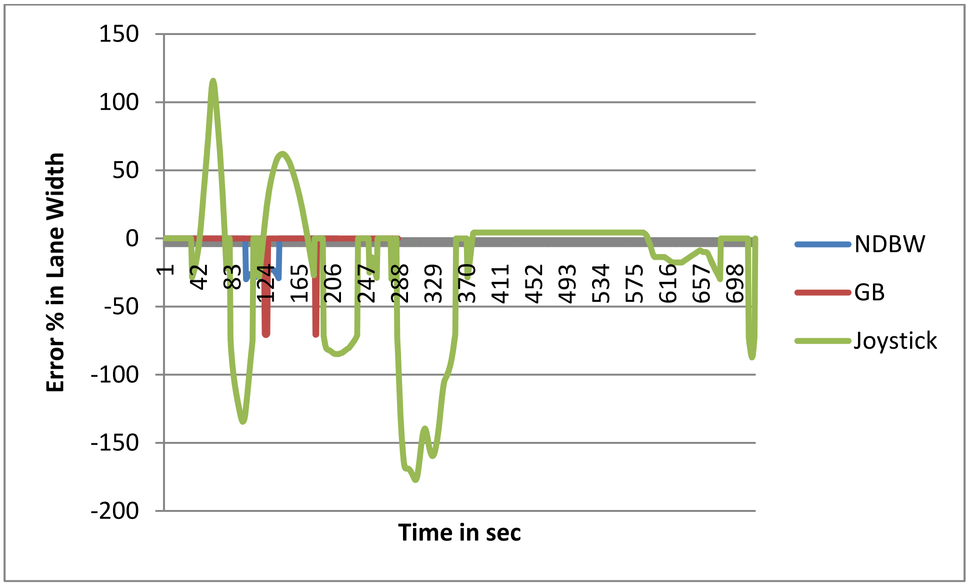


Figure A.23: Straight line steering results, Group II: participant 2

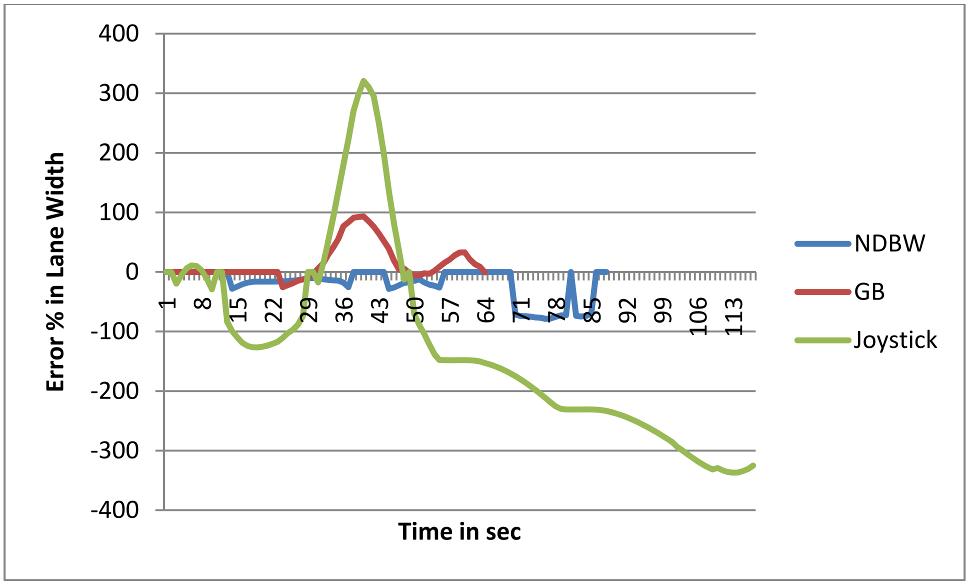


Figure A.24: Curved line steering results, Group II: participant 2

Appendix A: (Continued)

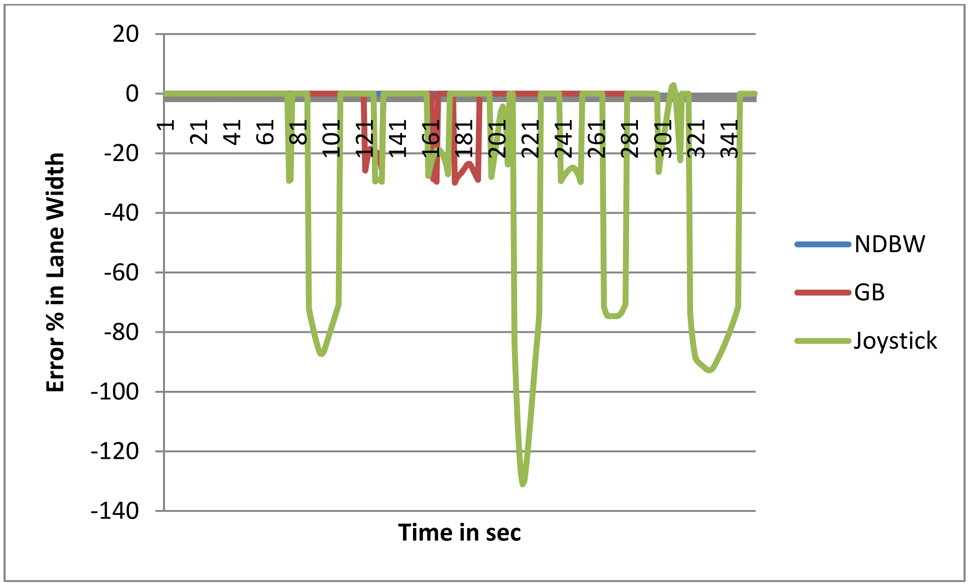


Figure A.25: Straight line steering results, Group II: participant 3

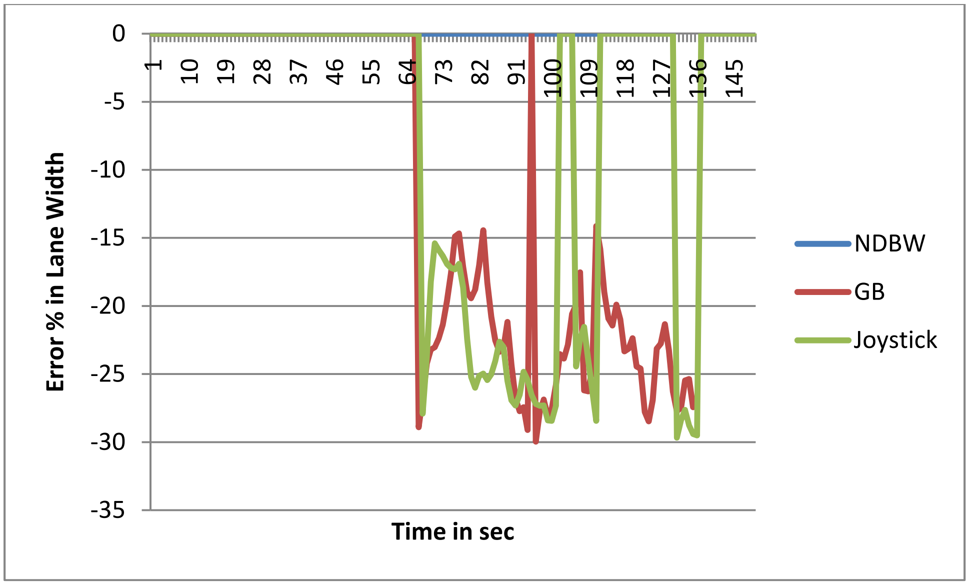


Figure A.26: Curved line steering results, Group II: participant 3

Appendix A: (Continued)

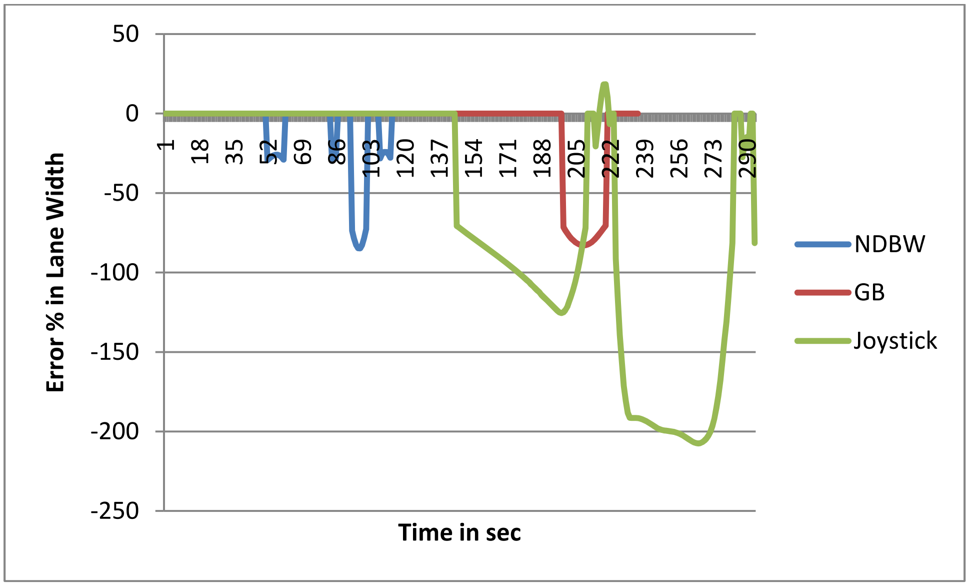


Figure A.27: Straight line steering results, Group II: participant 4

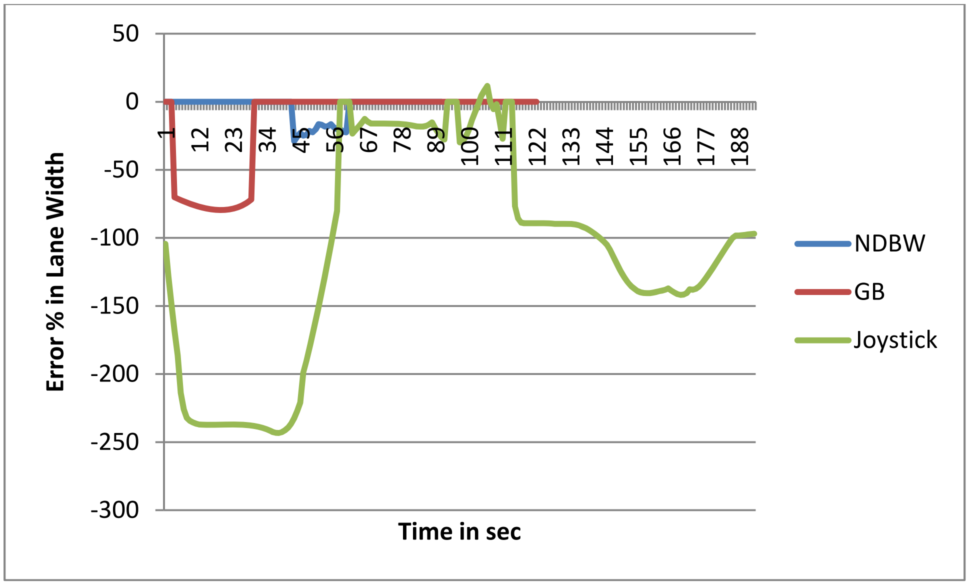


Figure A.28: Curved line steering results, Group II: participant 4

Appendix A: (Continued)

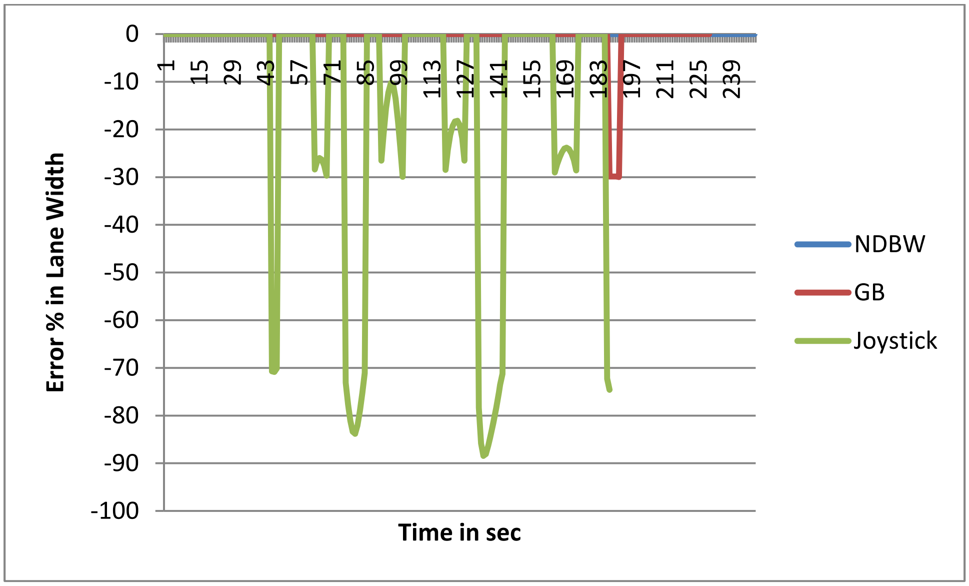


Figure A.29: Straight line steering results, Group II: participant 5

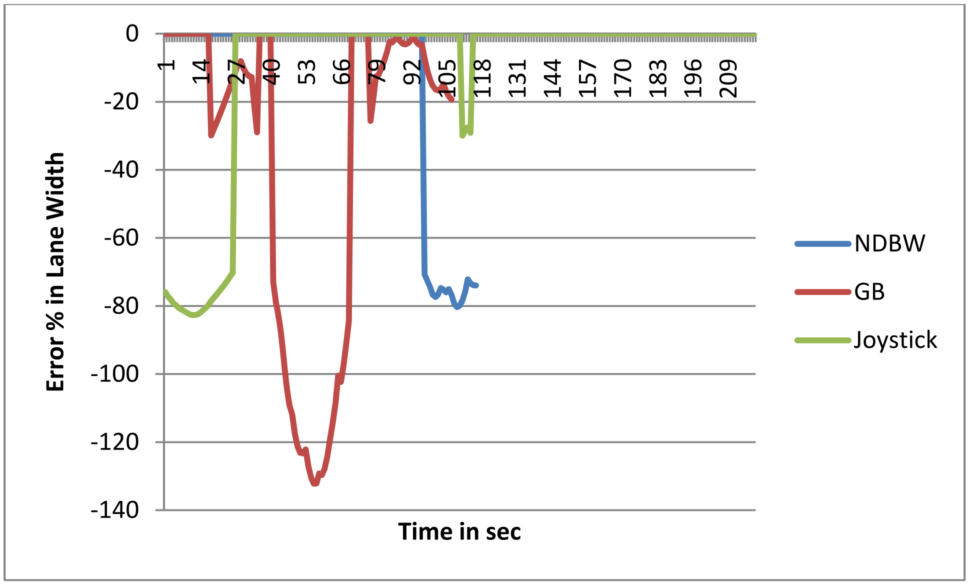


Figure A.30: Curved line steering results, Group II: participant 5

Appendix A: (Continued)

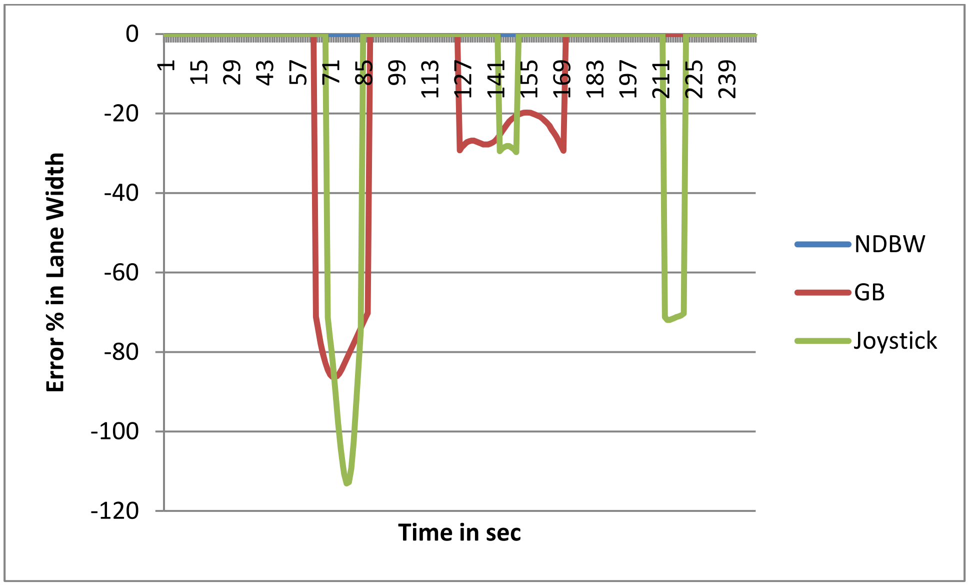


Figure A.31: Straight line steering results, Group II: participant 6

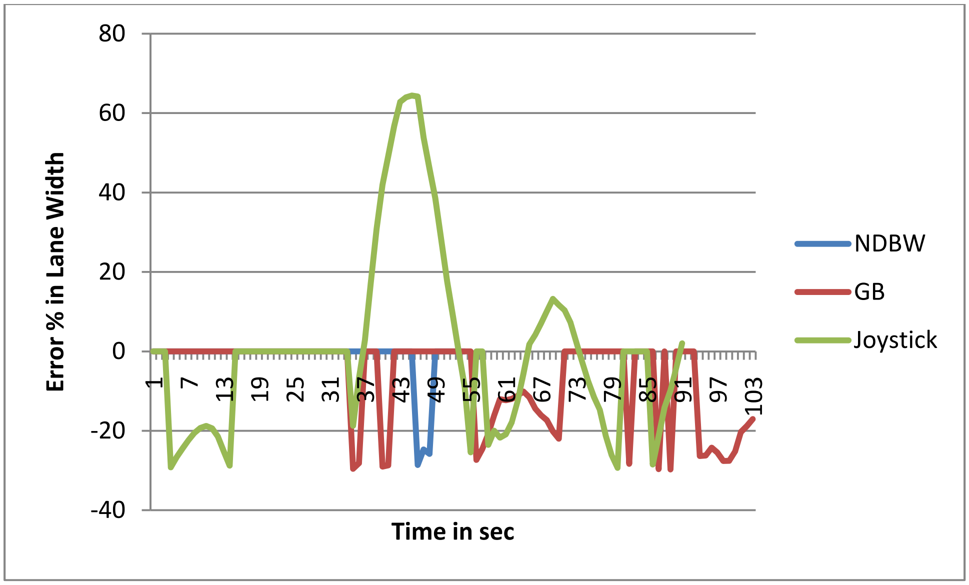


Figure A.32: Curved line steering results, Group II: participant 6

Appendix A: (Continued)

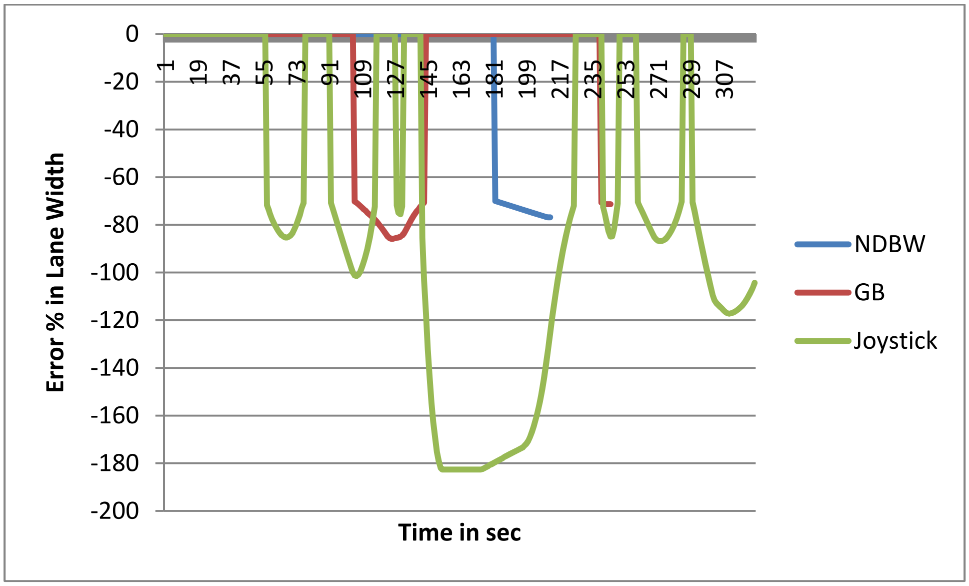


Figure A.33: Straight line steering results, Group II: participant 7

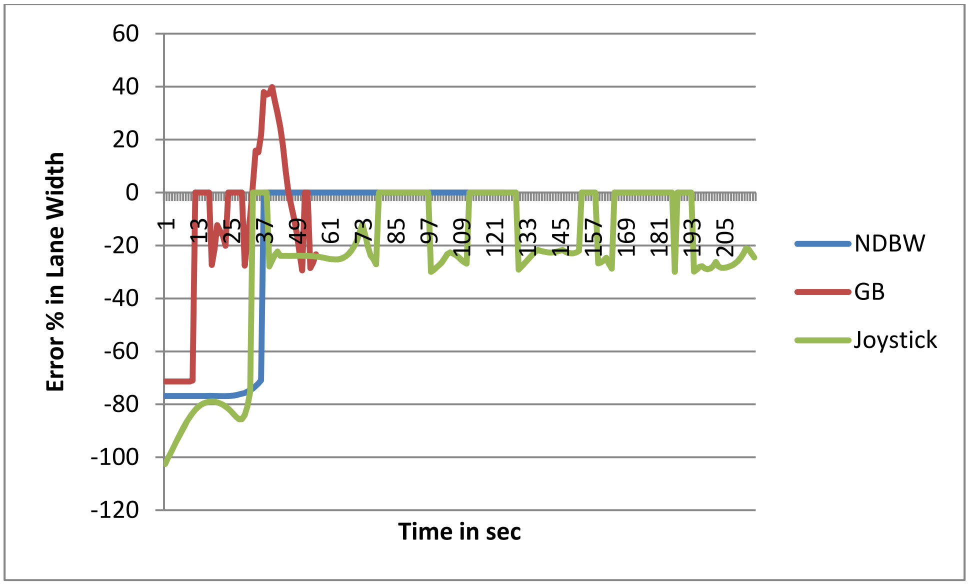


Figure A.34: Curved line steering results, Group II: participant 7

Appendix A: (Continued)

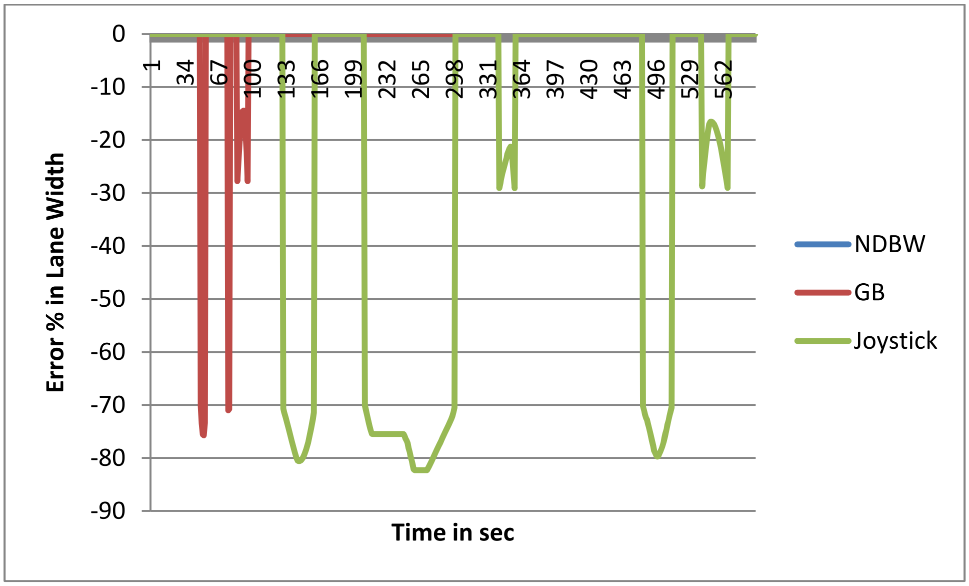


Figure A.35: Straight line steering results, Group II: participant 8

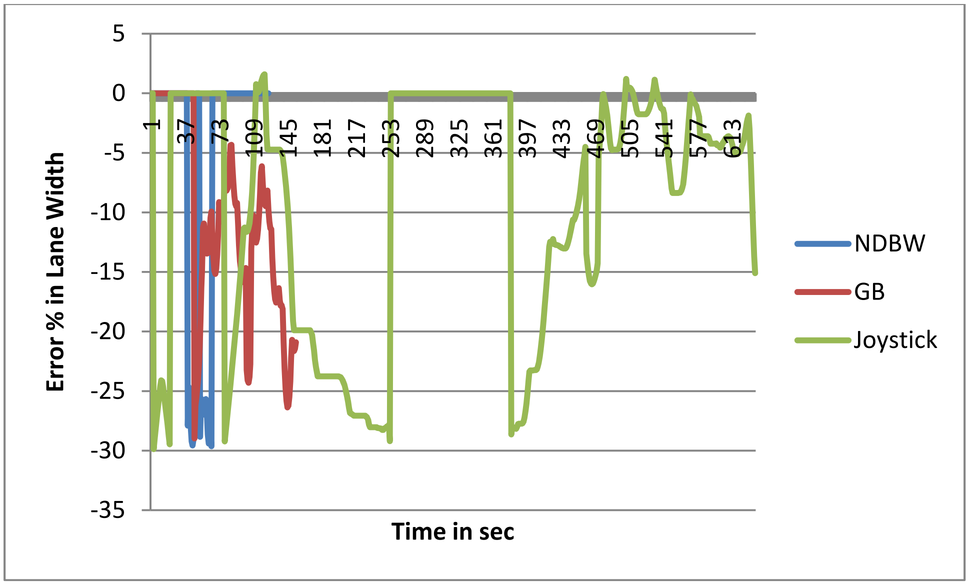


Figure A.36: Curved line steering results, Group II: participant 8

Appendix A: (Continued)

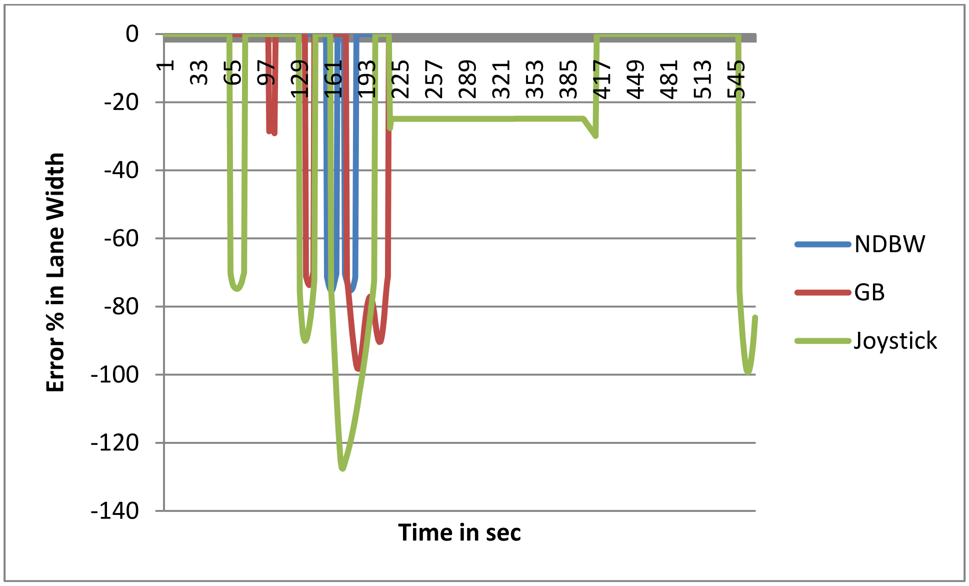


Figure A.37: Straight line steering results, Group II: participant 9

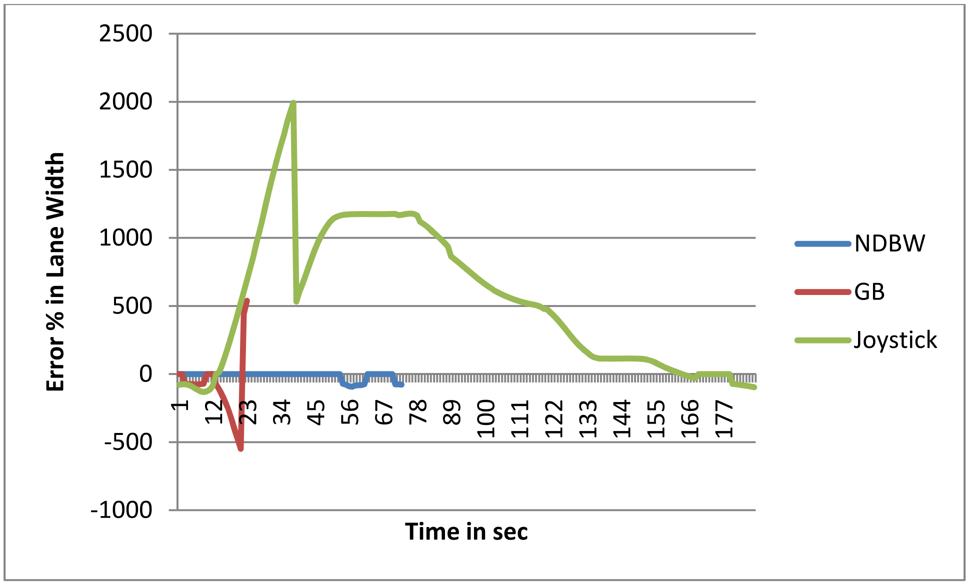


Figure A.38: Curved line steering results, Group II: participant 9

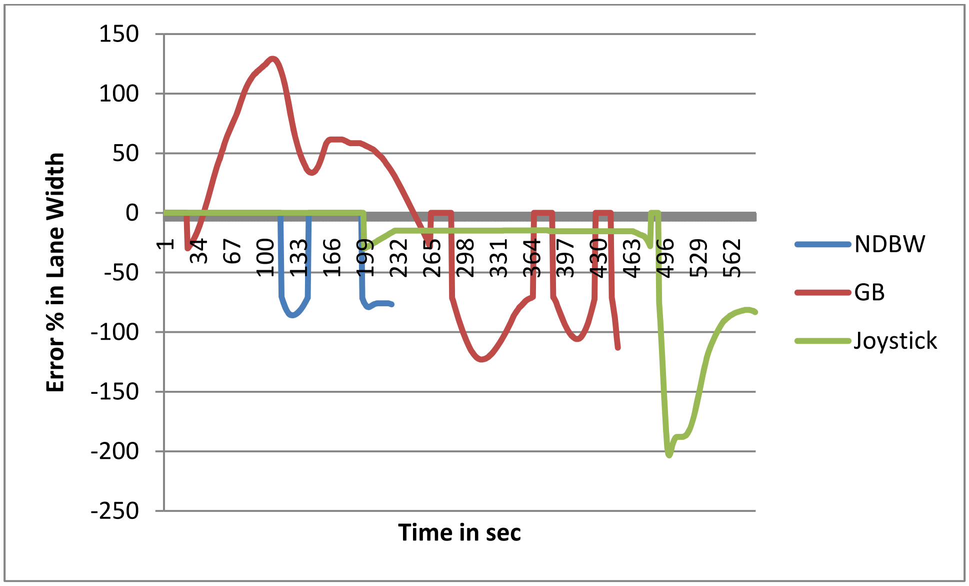


Figure A.39: Straight line steering results, Group II: participant 10

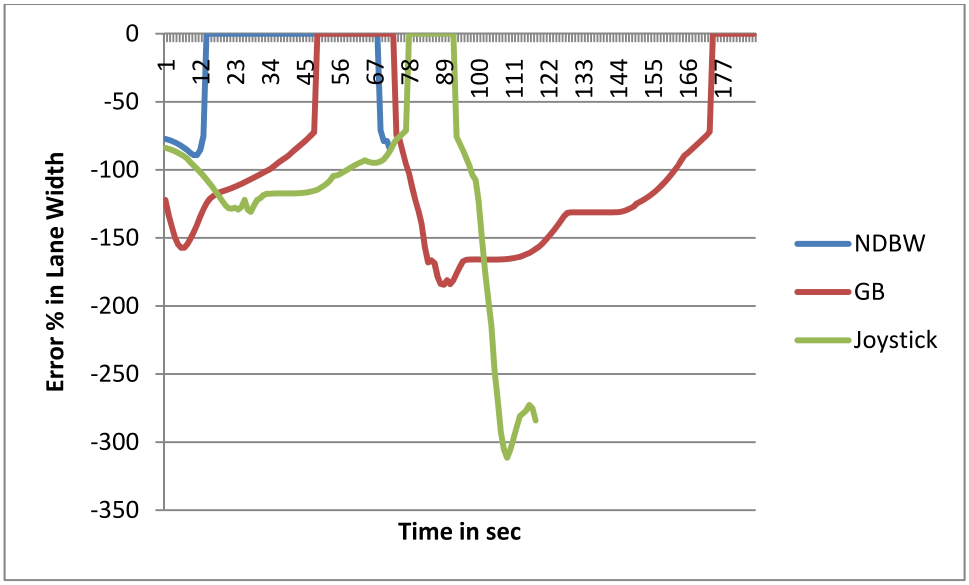


Figure A.40: Curved line steering results, Group II: participant 10

Appendix A: (Continued)

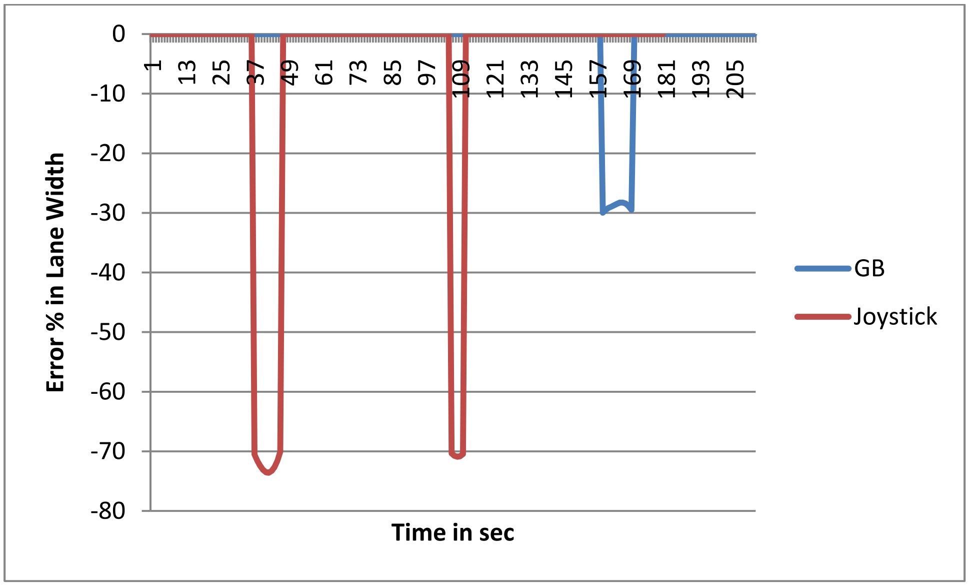


Figure A.41: Straight line steering results, Group III: participant 1

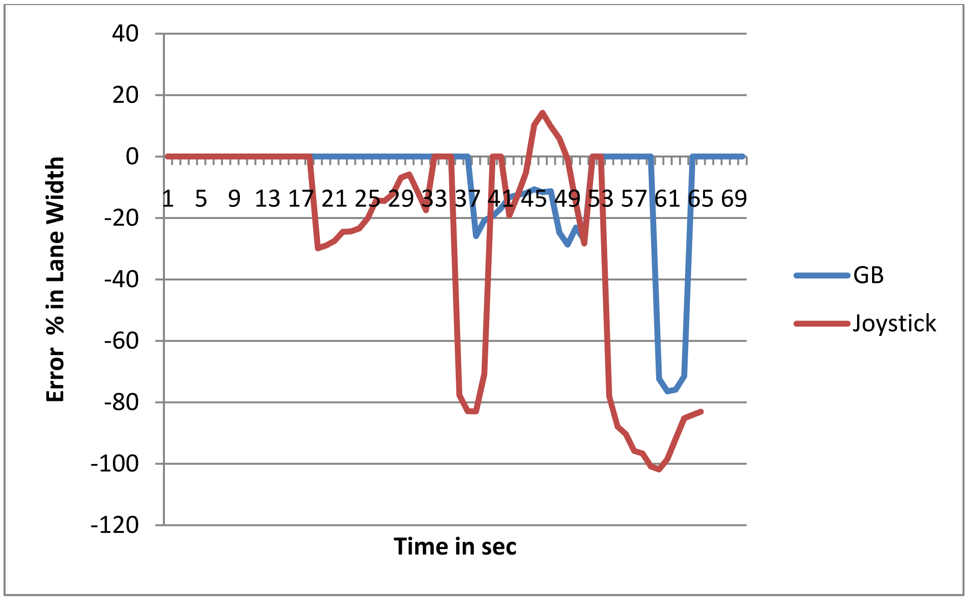


Figure A.42: Curved line steering results, Group III: participant 1

Appendix A: (Continued)

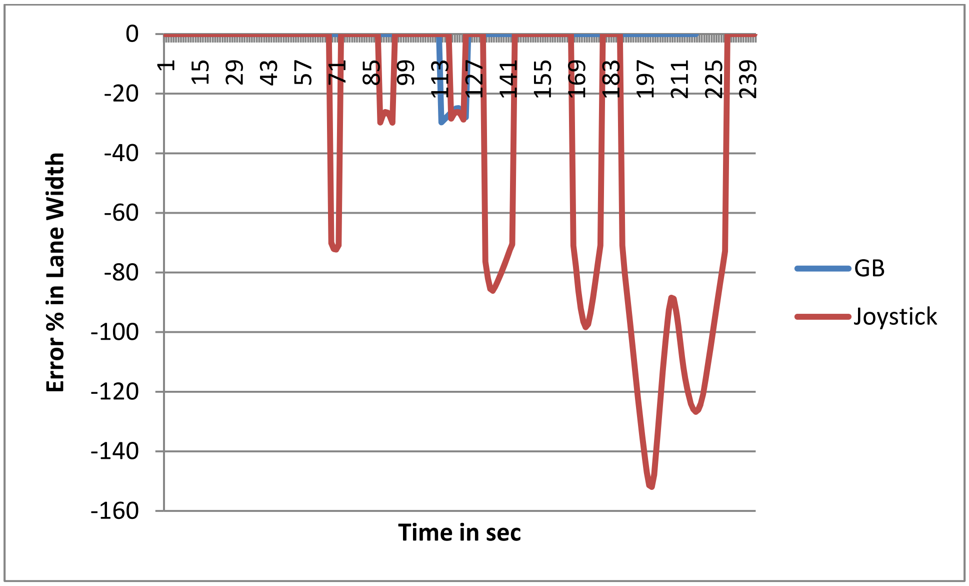


Figure A.43: Straight line steering results, Group III: participant 2

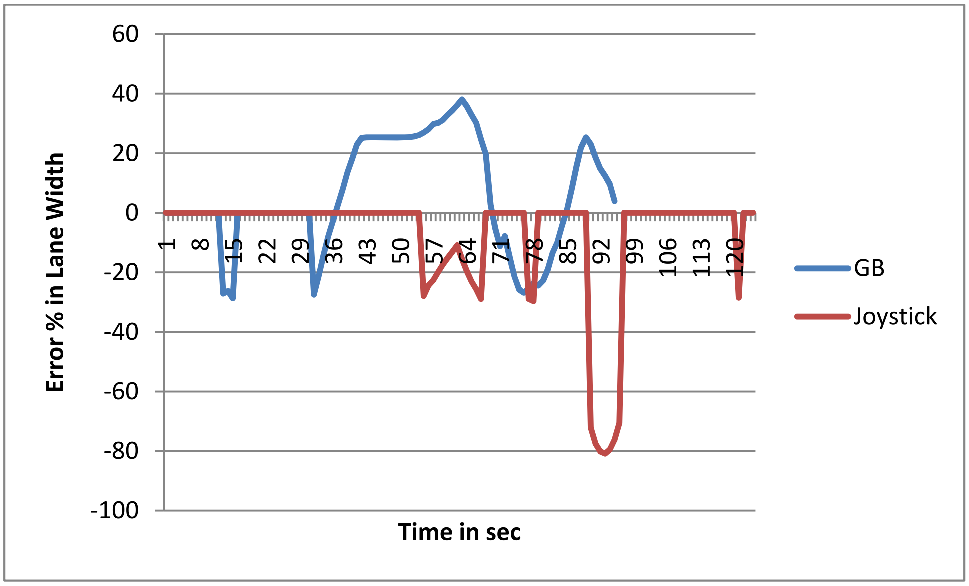


Figure A.44: Curved line steering results, Group III: participant 2

Appendix A: (Continued)

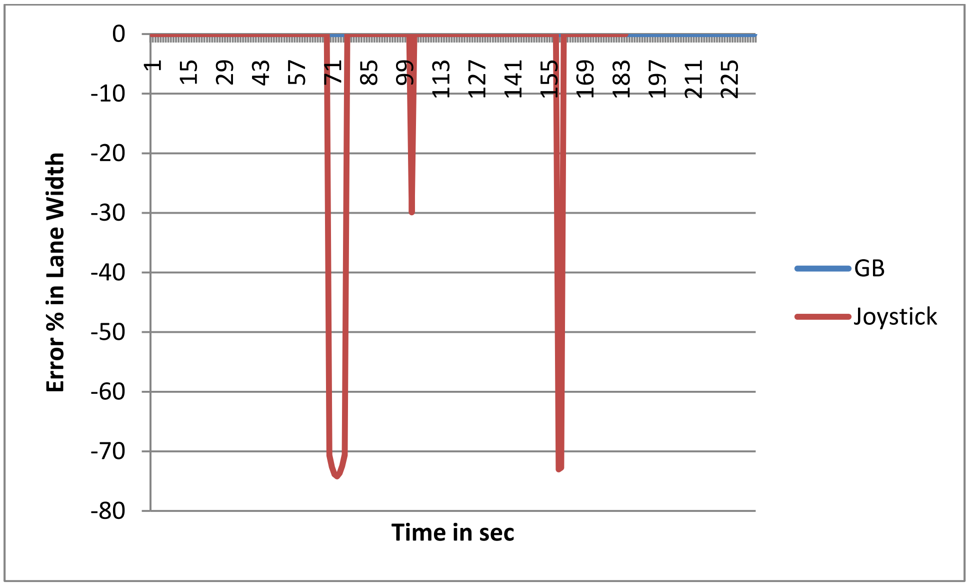


Figure A.45: Straight line steering results, Group III: participant 3

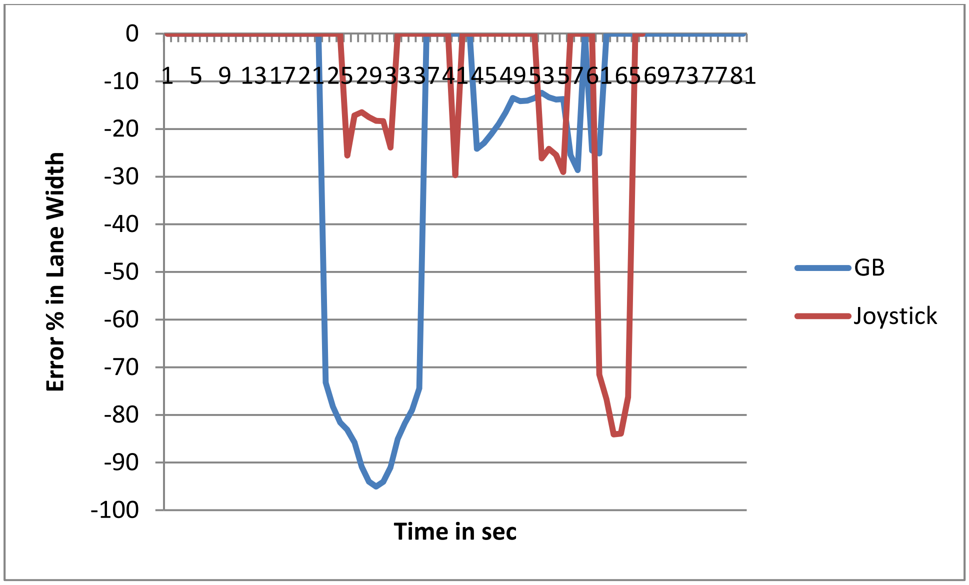


Figure A.46: Curved line steering results, Group III: participant 3

Appendix A: (Continued)

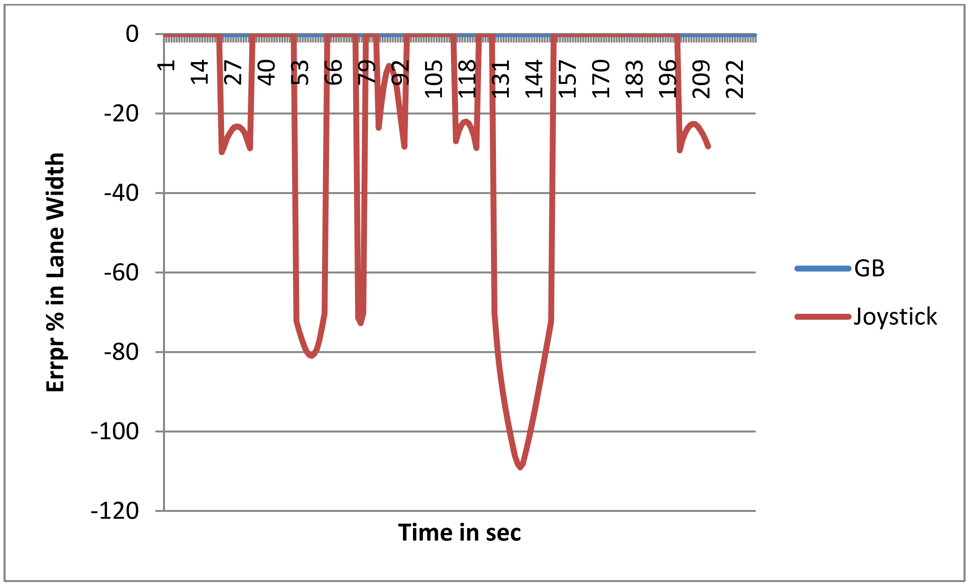


Figure A.47: Straight line steering results, Group III: participant 4

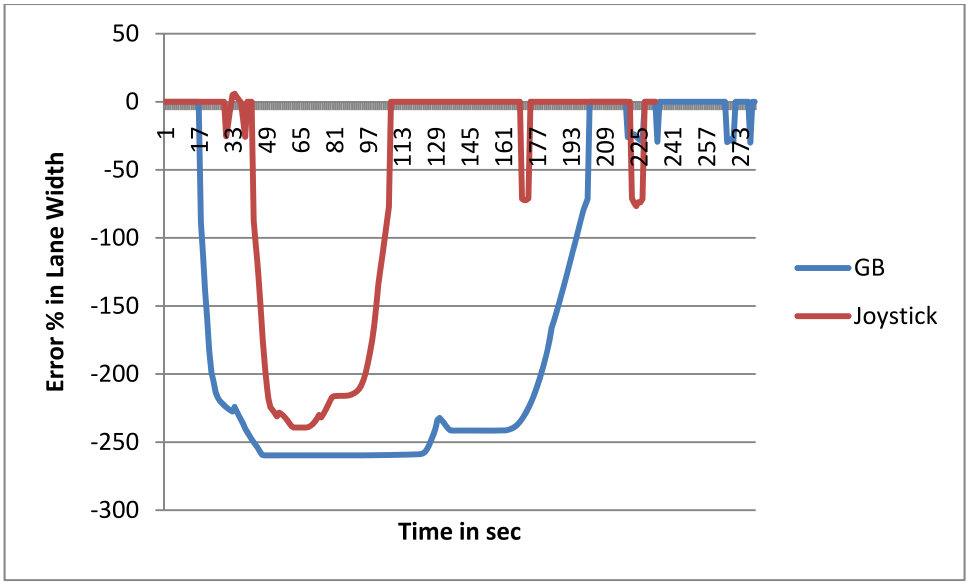


Figure A.48: Curved line steering results, Group III: participant 4

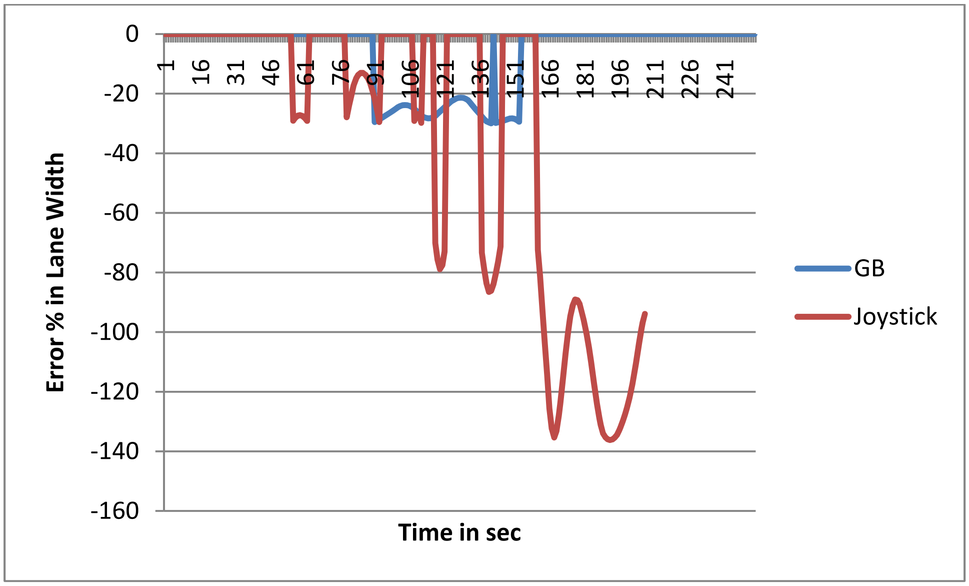


Figure A.49: Straight line steering results, Group III: participant 5

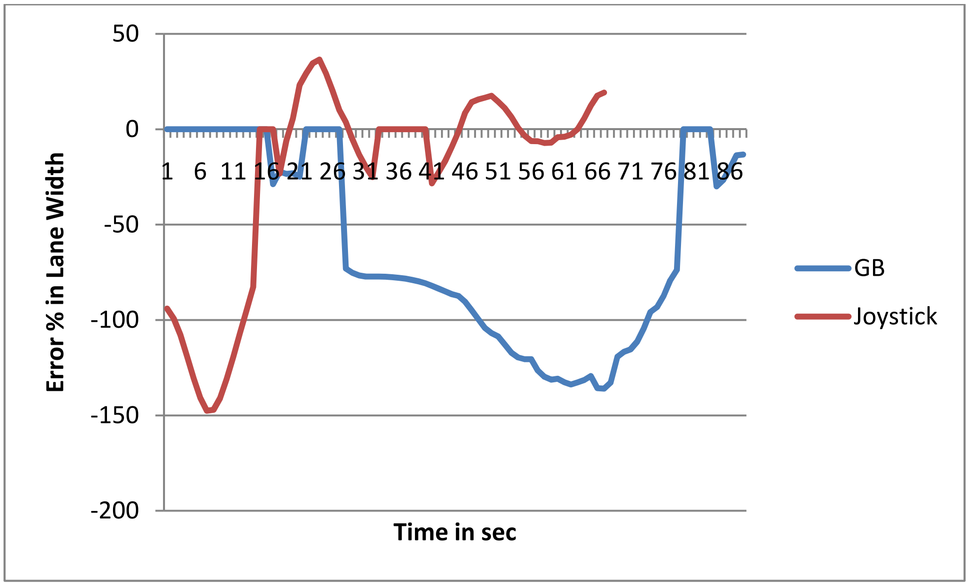


Figure A.50: Curved line steering results, Group III: participant 5

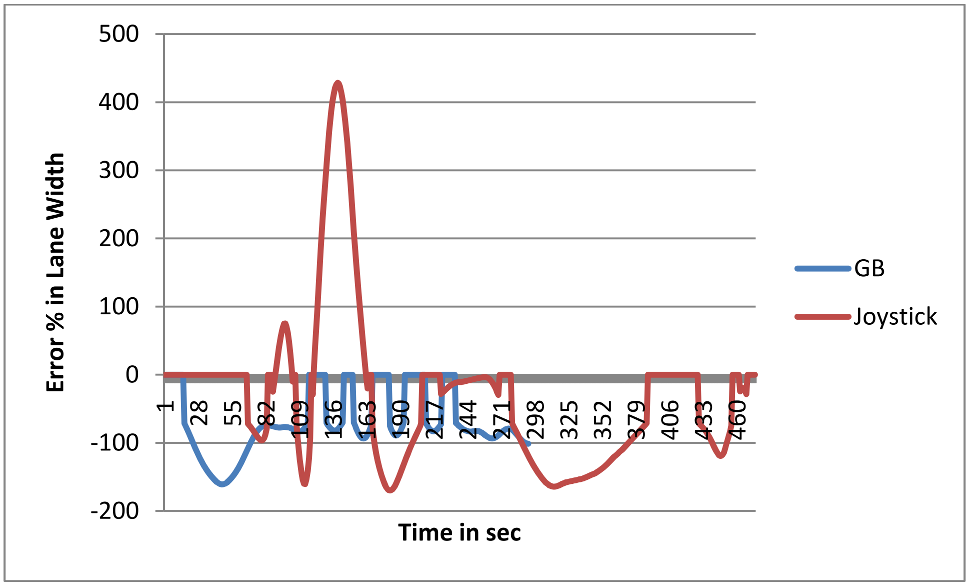


Figure A.51: Straight line steering results, Group III: participant 6

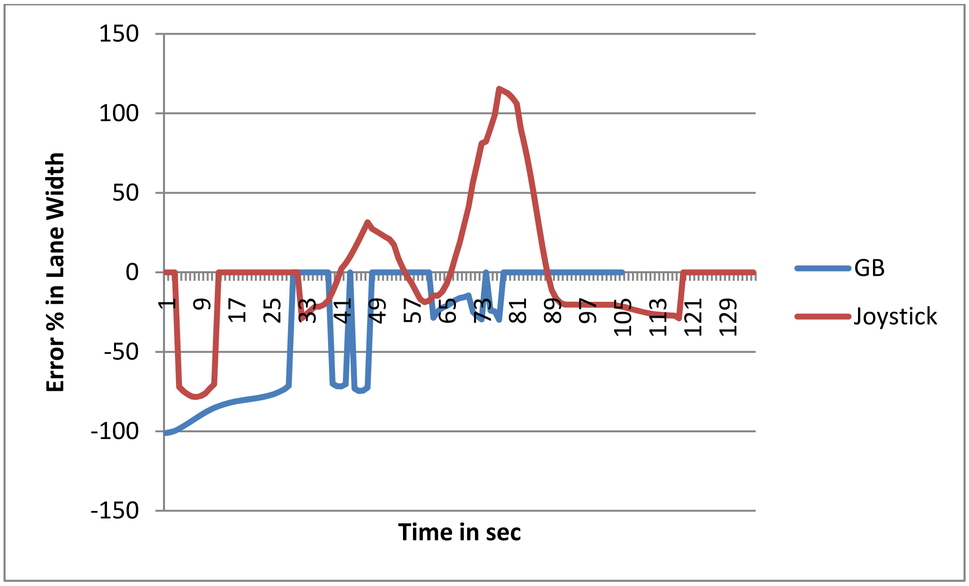


Figure A.52: Curved line steering results, Group III: participant 6

Appendix A: (Continued)

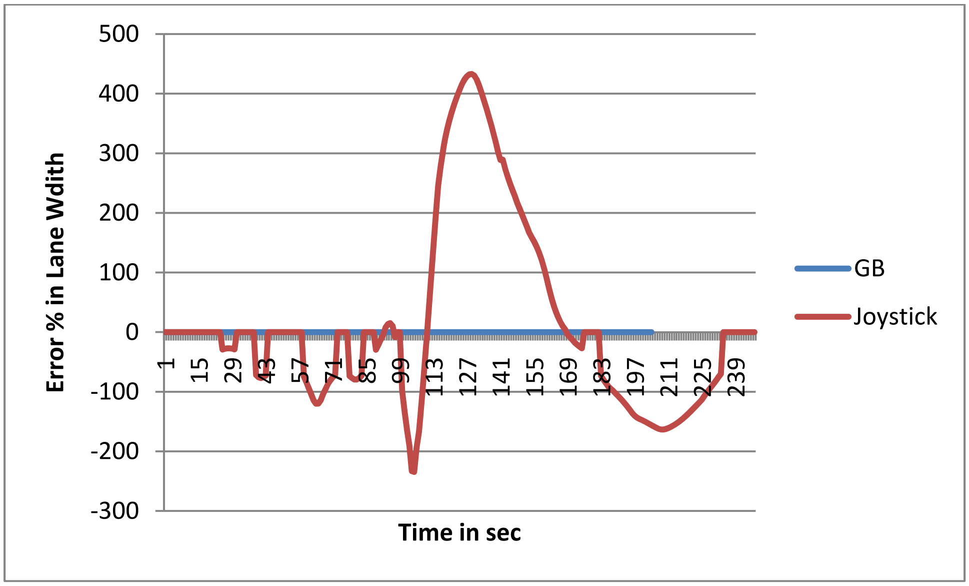


Figure A.53: Straight line steering results, Group III: participant 7

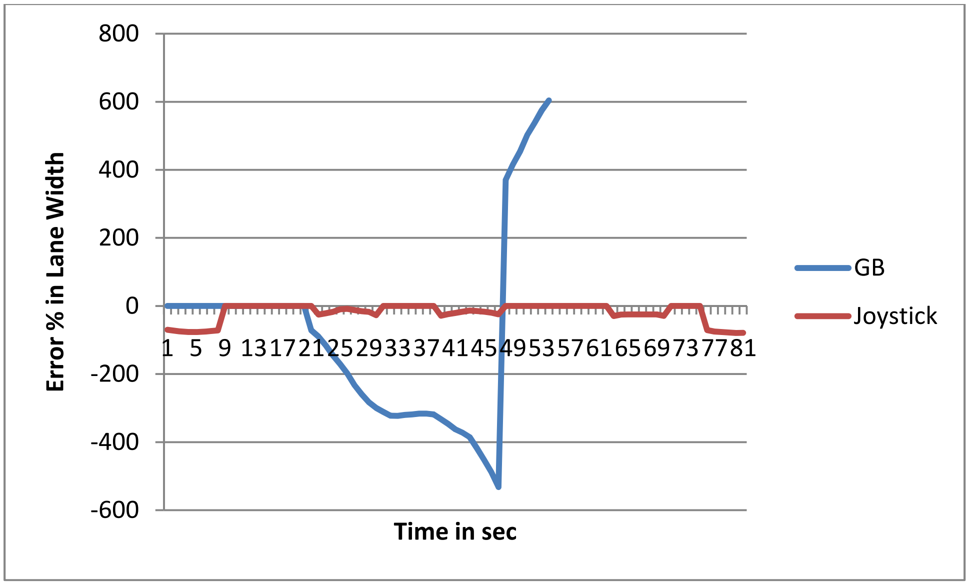


Figure A.54: Curved line steering results, Group III: participant 7

Appendix A: (Continued)

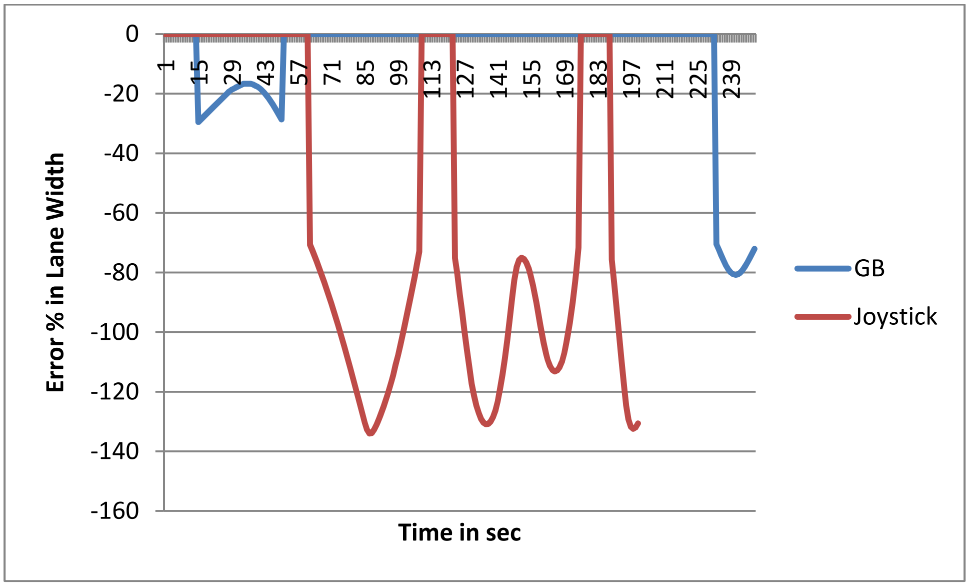


Figure A.55: Straight line steering results, Group III: participant 8

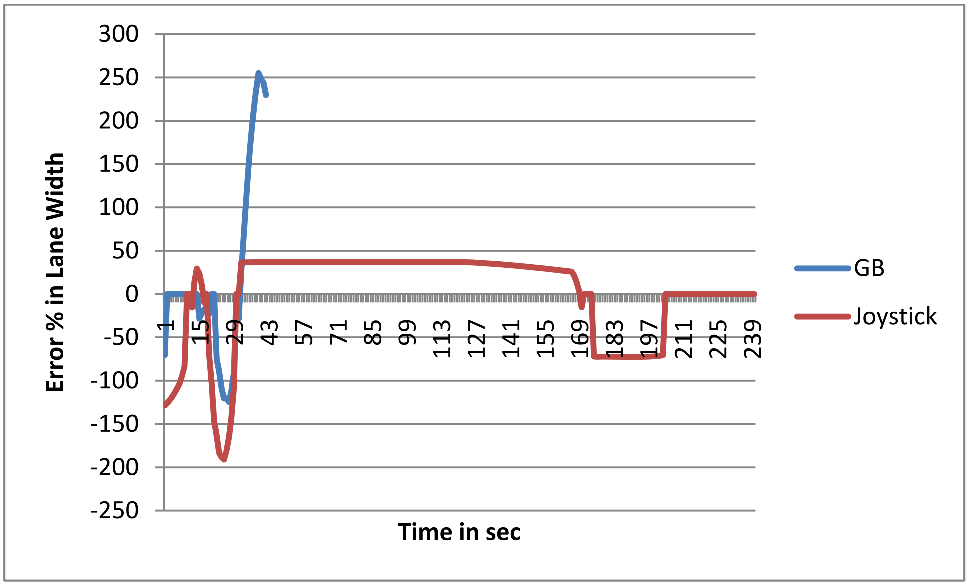


Figure A.56: Curved line steering results, Group III: participant 8

Appendix A: (Continued)

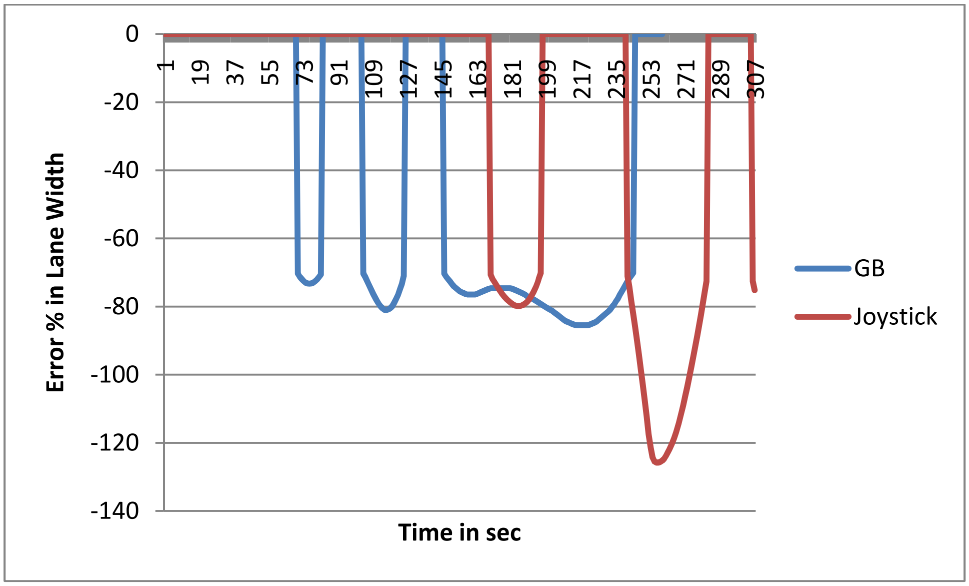


Figure A.57: Straight line steering results, Group III: participant 9

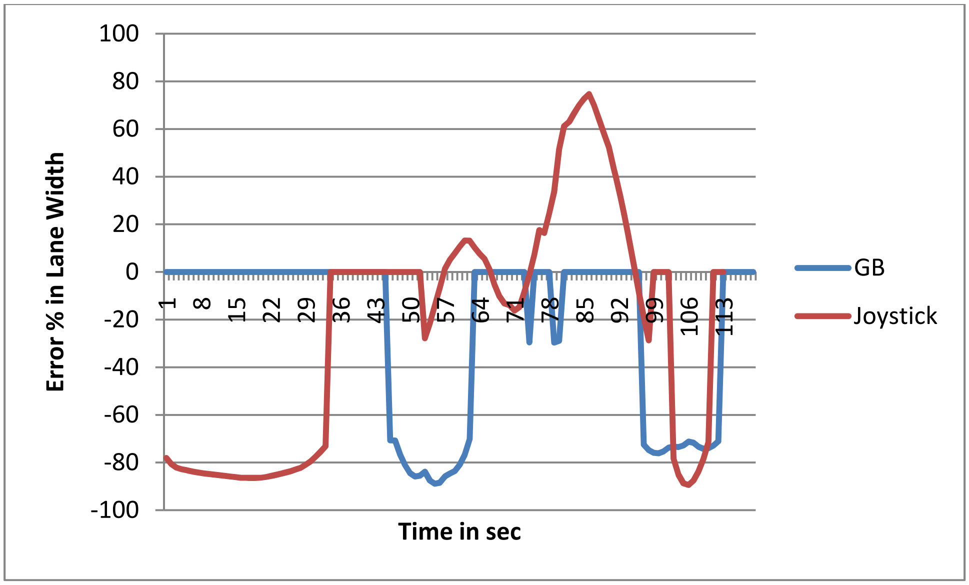


Figure A.58: Curved line steering results, Group III: participant 9

Appendix A: (Continued)

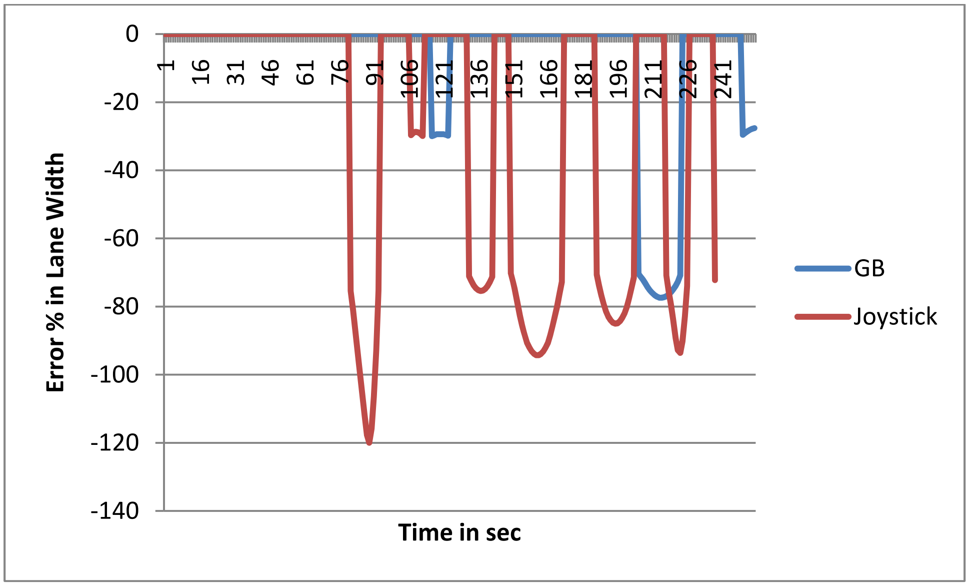


Figure A.59: Straight line steering results, Group III: participant 10

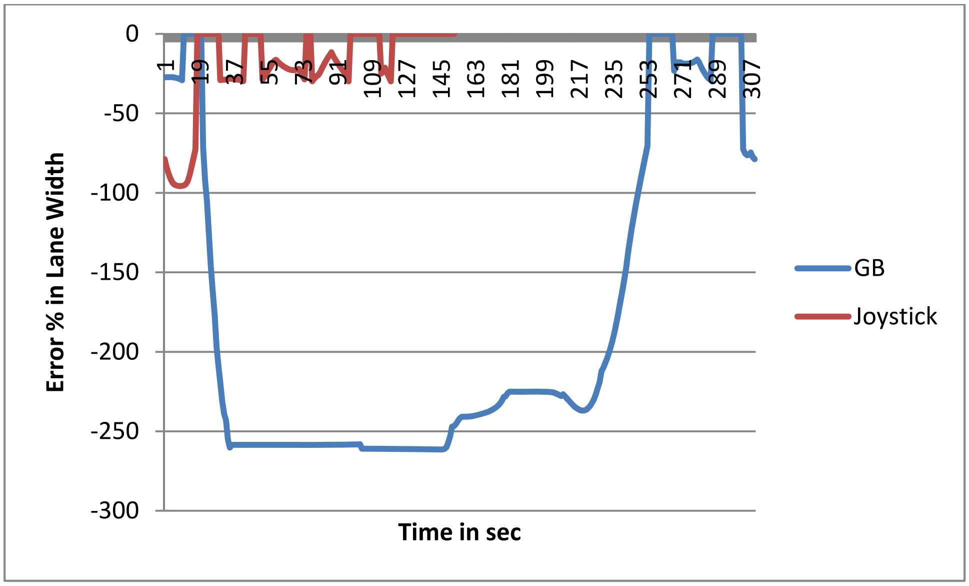


Figure A.60: Curved line steering results, Group III: participant 10

Appendix B: ANOVA Results for Rules Compliance

The following table shows the ANOVA results for the variables that do not have a significant difference in between the groups.

Table B.1: ANOVA results for rules compliance

ANOVA summary for Speed Infractions

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.713	2	3.857	2.607	0.08	3.12
Within Groups	109.5	74	1.479			
Total	117.2	76				

ANOVA summary for Inadequate Space Cushions

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.04	2	6.018	2.874	0.063	3.12
Within Groups	155	74	2.094			
Total	167	76				

ANOVA summary for Turn Signals Missed

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	138.9	2	69.47	1.941	0.151	3.12
Within Groups	2648	74	35.79			
Total	2787	76				

ANOVA summary for Dangerous Intersection Crossings

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.62	2	1.31	2.443	0.094	3.12
Within Groups	39.69	74	0.536			
Total	42.31	76				

ANOVA summary for Speed Infractions

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0	2	0	65535	#NUM!	3.12
Within Groups	0	74	0			
Total	0	76				

Appendix B: (Continued)

Table B.1: (Continued)

ANOVA summary for Inadequate Space Cushions

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.648	2	4.824	2.905	0.061	3.12
Within Groups	122.9	74	1.66			
Total	132.5	76				

ANOVA summary for Turn Signals Missed

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1328	2	664.2	10.18	1E-04	3.122
Within Groups	4763	73	65.24			
Total	6091	75				

ANOVA summary for Dangerous Intersection Crossings

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0	2	0	65535	#NUM!	3.122
Within Groups	0	73	0			
Total	0	75				

Appendix C: C++ Code to Evaluate Driver Steering Capabilities

```
        #include<stdio.h>
        #include <stdlib.h>
        #include <strings.h>

        #define NUMDATA 5000
        main(int argc, char*argv[])
        {  int j = 0, right = 0, left = 0, flag = 0, previousstretch = 0,
outcounter = 0;
           int i,k,lanew[NUMDATA],totalw[NUMDATA], position[NUMDATA], ij,
lefttime[NUMDATA], righttime[NUMDATA];
         FILE *fp = NULL, *fp2 = NULL;
         FILE * myout;
         char *filename;
         char headers[1000];
         if(argc > 1)
         {
            filename = argv[1];
         }
         else
         {
           fprintf(stderr,"\n Please provide Name of the Data file: ");
           char tmpfilename[100];
           gets(tmpfilename);
           filename = strdup(tmpfilename);
         }

         fp = fopen(filename, "r");
         if(!fp)
         {
             fprintf(stderr,"\n Unable to open file %s", filename);
             exit(1);
         }

        // Output File name


          char *opfilename = strdup(filename);
```

Appendix C: (Continued)

```
             opfilename[strlen(opfilename) -3] = 't';
             opfilename[strlen(opfilename) -2] = 'x';
             opfilename[strlen(opfilename) - 1] = 't';

          //End

            fp2 = fopen(opfilename,"w");
            if(!fp2)
            {
                fprintf(stderr,"\n Unable to open file: output.txt for writing.",
filename);
                exit(1);
            }

            myout = fp2;


             for( ij = 0; ij <5000; ij++)
             {
                   lanew[ij] = totalw[ij] = position[ij] = lefttime[ij] = righttime[ij]
= 0;
             }

            /* Scan the header. The third line is the labels for the columns.
Ignore them for now */


            fgets(headers, 1000, fp);
            fgets(headers,1000,fp);
            fgets(headers, 1000, fp);

           /* Start reading the data */

            i=0;k=0;
            while(1)
            {
              int ret = 0, v1=0,v2=0;
              ret = fscanf(fp,"%d", &lanew[i]);

           ret = fscanf(fp,"%d", &totalw[i]);
```

```
      ret = fscanf(fp,"%d", &position[i++]);
        if( ret == EOF || ret <= 0)
        {
            i--;
            break;
        }

       }


       while( j <= i)
       {

         fprintf(myout,"\n a[%d] = %d",j,totalw[j]);
         switch(totalw[j])
         {
             case 3000:
                   if( previousstretch != 3000 )
                   {
                        fprintf(myout," Changing roads\n");
                   }
                   if(position[j] < 900)
                   {
                      left++;
                      while(position[++j] < 900  && totalw[j] == 3000)
                     {
                        lefttime[outcounter]++;
      //fprintf(stderr,"\n position[%d] = %d;  left+1 = %d",j, position[j],
lefttime[outcounter]);
                        flag = 1;
                     }
                     fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                   }
                   else if(position[j] > 2100)
                   {
                      right++;
                      while(position[++j] > 2100 && totalw[j] == 3000)
{righttime[outcounter]++; flag = 1;}
```

```
            fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                      }
                      previousstretch = 3000;
                      if(flag)
                      { flag = 0; outcounter++;}

                      break;
              case 2500:
                      if( previousstretch != 2500 )
                      {
                           fprintf(myout," Changing roads\n");
                      }
                      if(position[j] < 900)
                      {
                          left++;
                          while(position[++j] < 900  && totalw[j] ==
2500){lefttime[outcounter]++; flag = 1;}
                        fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                      }
                      else if(position[j] > 1600)
                      {
                          right++;
                          while(position[++j] > 1600 && totalw[j] == 2500)
{righttime[outcounter]++; flag = 1;}
                        fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                      }
                      previousstretch = 2500;
                      if(flag)
                      { flag = 0; outcounter++;}

                      break;
              case 3500:
                      if( previousstretch != 3500 )
                      {
                           fprintf(myout," Changing roads\n");
                      }
                      if(position[j] < 900)
```

Appendix C: (Continued)

```
         {
                              left++;
                              while(position[++j] < 900  && totalw[j] ==
3500){lefttime[outcounter]++; flag = 1;}
                            fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                          }
                          else if(position[j] > 2600)
                          {
                              right++;
                              while(position[++j] > 2600  && totalw[j] == 3500)
{righttime[outcounter]++; flag = 1;}
                            fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                          }
                          previousstretch = 3500;
                          if(flag)
                          { flag = 0; outcounter++;}
                          break;
                 case 7000:
                          if( previousstretch != 7000 )
                          {
                                fprintf(myout," Changing roads\n");
                          }
                          if(position[j] < 900)
                          {
                              left++;
                              while(position[++j] < 900  && totalw[j] ==
7000){lefttime[outcounter]++; flag = 1;}
                            fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                          }
                          else if(position[j] > 6100)
                          {
                              right++;
                              while(position[++j] > 6100  && totalw[j] == 7000)
{righttime[outcounter]++; flag = 1;}
                            fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                          }
```

Appendix C: (Continued)

```
                previousstretch = 7000;
                       if(flag)
                       { flag = 0; outcounter++;}
                       break;
               case 4000:
                       if( previousstretch != 4000 )
                       {
                             fprintf(myout," Changing roads\n");
                       }
                       if(position[j] < 900)
                       {
                           left++;
                           while(position[++j] < 900 && totalw[j] ==
4000){lefttime[outcounter]++; flag = 1;}
                         fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                       }
                       else if(position[j] > 3100)
                       {
                           right++;
                           while(position[++j] > 3100  && totalw[j] == 4000)
{righttime[outcounter]++; flag = 1;}
                         fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                       }
                       previousstretch = 4000;
                       if(flag)
                       { flag = 0; outcounter++;}

                       break;
               case 4500:
                       if( previousstretch != 4500 )
                       {
                             fprintf(myout," Changing roads\n");
                       }
                       if(position[j] < 900)
                       {
                           left++;
                           while(position[++j] < 900 && totalw[j] ==
4500){lefttime[outcounter]++; flag = 1;}
```

Appendix C: (Continued)

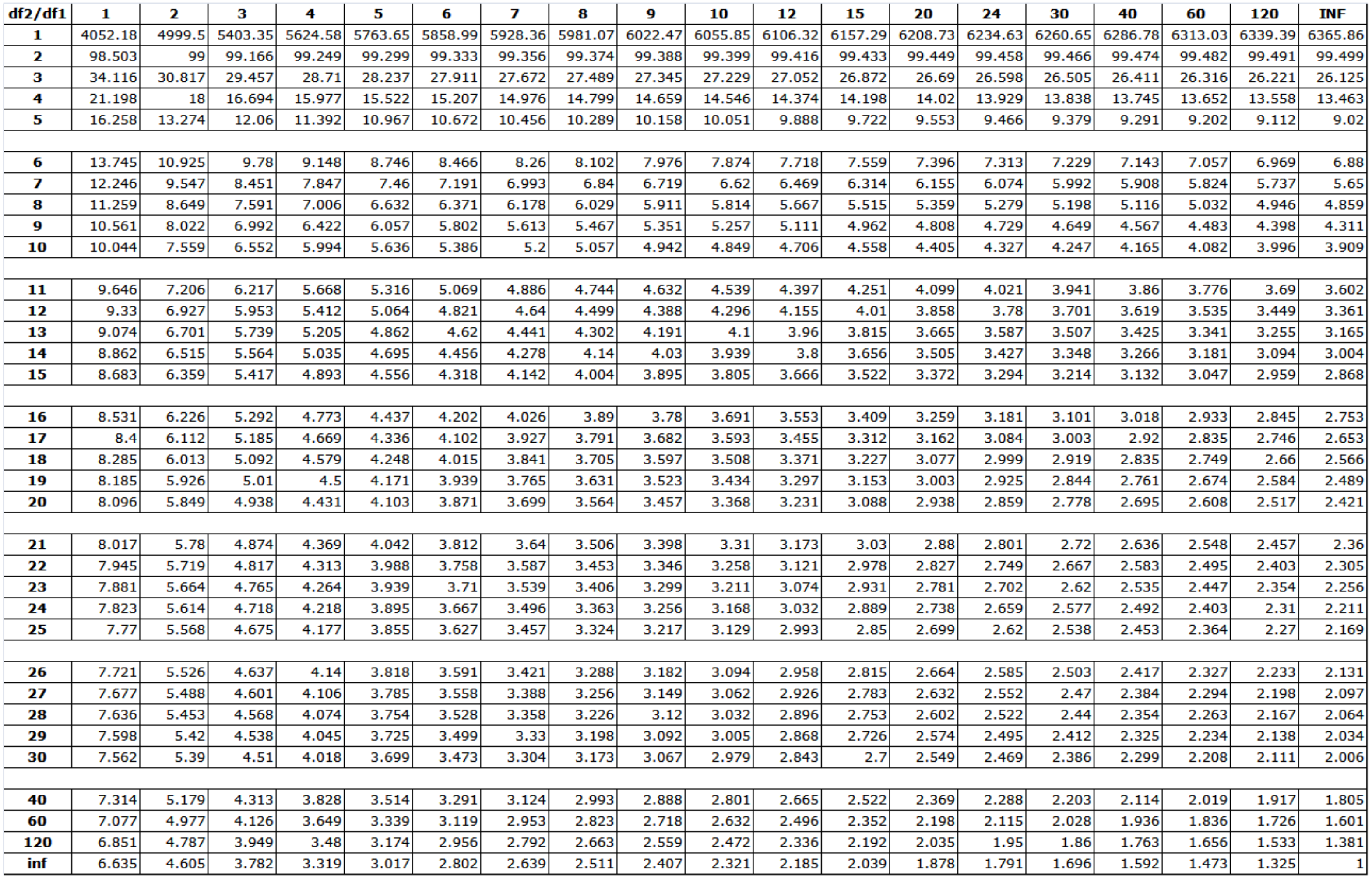
```
                             fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                           }
                           else if(position[j] > 3600)
                           {
                               right++;
                               while(position[++j] > 3600 && totalw[j] == 4500)
{righttime[outcounter]++; flag = 1;}
                             fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                           }
                           previousstretch = 4500;
                           if(flag)
                           { flag = 0; outcounter++;}

                           break;
                  case 8000:
                            if( previousstretch != 8000 )
                           {
                                   fprintf(myout," Changing roads\n");
                           }
                           if(position[j] < 900)
                           {
                               left++;
                               while(position[++j] < 900 && totalw[j] ==
8000){lefttime[outcounter]++; flag = 1;}
                             fprintf(myout,"\n Went left for %f seconds",
(lefttime[outcounter] + 1)/5.0);
                           }
                           else if(position[j] > 7100)
                           {
                               right++;
                               while(position[++j] > 7100 && totalw[j] == 8000)
{righttime[outcounter]++; flag = 1;}
                             fprintf(myout,"\n Went right for %f seconds",
(righttime[outcounter] + 1)/5.0);
                           }
                           previousstretch = 8000;
                           if(flag)
                           { flag = 0; outcounter++;}
```

Appendix C: (Continued)

```
                        break;

                default:
                    fprintf(myout,"\n Error! New Width. Need to add case
here.");
                    break;
            }
            j++;

          }

         fprintf(myout,"\n right = %d\n left = %d",right,left);

         return(0);

        }
```

Appendix D: F-Critical Value Table for p<0.01

Table D1: F-table for p<0.01



df2/df1	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	INF
1	4052.18	4999.5	5403.35	5624.58	5763.65	5858.99	5928.36	5981.07	6022.47	6055.85	6106.32	6157.29	6208.73	6234.63	6260.65	6286.78	6313.03	6339.39	6365.86
2	98.503	99	99.166	99.249	99.299	99.333	99.356	99.374	99.388	99.399	99.416	99.433	99.449	99.458	99.466	99.474	99.482	99.491	99.499
3	34.116	30.817	29.457	28.71	28.237	27.911	27.672	27.489	27.345	27.229	27.052	26.872	26.69	26.598	26.505	26.411	26.316	26.221	26.125
4	21.198	18	16.694	15.977	15.522	15.207	14.976	14.799	14.659	14.546	14.374	14.198	14.02	13.929	13.838	13.745	13.652	13.558	13.463
5	16.258	13.274	12.06	11.392	10.967	10.672	10.456	10.289	10.158	10.051	9.888	9.722	9.553	9.466	9.379	9.291	9.202	9.112	9.02
6	13.745	10.925	9.78	9.148	8.746	8.466	8.26	8.102	7.976	7.874	7.718	7.559	7.396	7.313	7.229	7.143	7.057	6.969	6.88
7	12.246	9.547	8.451	7.847	7.46	7.191	6.993	6.84	6.719	6.62	6.469	6.314	6.155	6.074	5.992	5.908	5.824	5.737	5.65
8	11.259	8.649	7.591	7.006	6.632	6.371	6.178	6.029	5.911	5.814	5.667	5.515	5.359	5.279	5.198	5.116	5.032	4.946	4.859
9	10.561	8.022	6.992	6.422	6.057	5.802	5.613	5.467	5.351	5.257	5.111	4.962	4.808	4.729	4.649	4.567	4.483	4.398	4.311
10	10.044	7.559	6.552	5.994	5.636	5.386	5.2	5.057	4.942	4.849	4.706	4.558	4.405	4.327	4.247	4.165	4.082	3.996	3.909
11	9.646	7.206	6.217	5.668	5.316	5.069	4.886	4.744	4.632	4.539	4.397	4.251	4.099	4.021	3.941	3.86	3.776	3.69	3.602
12	9.33	6.927	5.953	5.412	5.064	4.821	4.64	4.499	4.388	4.296	4.155	4.01	3.858	3.78	3.701	3.619	3.535	3.449	3.361
13	9.074	6.701	5.739	5.205	4.862	4.62	4.441	4.302	4.191	4.1	3.96	3.815	3.665	3.587	3.507	3.425	3.341	3.255	3.165
14	8.862	6.515	5.564	5.035	4.695	4.456	4.278	4.14	4.03	3.939	3.8	3.656	3.505	3.427	3.348	3.266	3.181	3.094	3.004
15	8.683	6.359	5.417	4.893	4.556	4.318	4.142	4.004	3.895	3.805	3.666	3.522	3.372	3.294	3.214	3.132	3.047	2.959	2.868
16	8.531	6.226	5.292	4.773	4.437	4.202	4.026	3.89	3.78	3.691	3.553	3.409	3.259	3.181	3.101	3.018	2.933	2.845	2.753
17	8.4	6.112	5.185	4.669	4.336	4.102	3.927	3.791	3.682	3.593	3.455	3.312	3.162	3.084	3.003	2.92	2.835	2.746	2.653
18	8.285	6.013	5.092	4.579	4.248	4.015	3.841	3.705	3.597	3.508	3.371	3.227	3.077	2.999	2.919	2.835	2.749	2.66	2.566
19	8.185	5.926	5.01	4.5	4.171	3.939	3.765	3.631	3.523	3.434	3.297	3.153	3.003	2.925	2.844	2.761	2.674	2.584	2.489
20	8.096	5.849	4.938	4.431	4.103	3.871	3.699	3.564	3.457	3.368	3.231	3.088	2.938	2.859	2.778	2.695	2.608	2.517	2.421
21	8.017	5.78	4.874	4.369	4.042	3.812	3.64	3.506	3.398	3.31	3.173	3.03	2.88	2.801	2.72	2.636	2.548	2.457	2.36
22	7.945	5.719	4.817	4.313	3.988	3.758	3.587	3.453	3.346	3.258	3.121	2.978	2.827	2.749	2.667	2.583	2.495	2.403	2.305
23	7.881	5.664	4.765	4.264	3.939	3.71	3.539	3.406	3.299	3.211	3.074	2.931	2.781	2.702	2.62	2.535	2.447	2.354	2.256
24	7.823	5.614	4.718	4.218	3.895	3.667	3.496	3.363	3.256	3.168	3.032	2.889	2.738	2.659	2.577	2.492	2.403	2.31	2.211
25	7.77	5.568	4.675	4.177	3.855	3.627	3.457	3.324	3.217	3.129	2.993	2.85	2.699	2.62	2.538	2.453	2.364	2.27	2.169
26	7.721	5.526	4.637	4.14	3.818	3.591	3.421	3.288	3.182	3.094	2.958	2.815	2.664	2.585	2.503	2.417	2.327	2.233	2.131
27	7.677	5.488	4.601	4.106	3.785	3.558	3.388	3.256	3.149	3.062	2.926	2.783	2.632	2.552	2.47	2.384	2.294	2.198	2.097
28	7.636	5.453	4.568	4.074	3.754	3.528	3.358	3.226	3.12	3.032	2.896	2.753	2.602	2.522	2.44	2.354	2.263	2.167	2.064
29	7.598	5.42	4.538	4.045	3.725	3.499	3.33	3.198	3.092	3.005	2.868	2.726	2.574	2.495	2.412	2.325	2.234	2.138	2.034
30	7.562	5.39	4.51	4.018	3.699	3.473	3.304	3.173	3.067	2.979	2.843	2.7	2.549	2.469	2.386	2.299	2.208	2.111	2.006
40	7.314	5.179	4.313	3.828	3.514	3.291	3.124	2.993	2.888	2.801	2.665	2.522	2.369	2.288	2.203	2.114	2.019	1.917	1.805
60	7.077	4.977	4.126	3.649	3.339	3.119	2.953	2.823	2.718	2.632	2.496	2.352	2.198	2.115	2.028	1.936	1.836	1.726	1.601
120	6.851	4.787	3.949	3.48	3.174	2.956	2.792	2.663	2.559	2.472	2.336	2.192	2.035	1.95	1.86	1.763	1.656	1.533	1.381
inf	6.635	4.605	3.782	3.319	3.017	2.802	2.639	2.511	2.407	2.321	2.185	2.039	1.878	1.791	1.696	1.592	1.473	1.325	1