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Testing and Evaluation of a Novel Virtual Reality Integrated Adaptive Driving System

Matthew R. Fowler
University of South Florida

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by

Matthew R. Fowler

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Major Professor: Rajiv Dubey, Ph.D.
Kathryn DeLaurentis, Ph.D.
Shuh-Jing Ying, Ph.D.

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- *For I can do all things through Christ who strengthens me. Philippians 4:13*

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ABSTRACT

Virtual simulators have proven to be extremely effective tools for training individuals for tasks that might otherwise be cost-prohibitive, dangerous, or impractical. One advantage of using a virtual simulator is that it provides a safe environment for emergency scenarios. For many years the United States military and NASA have used simulators, including those affixed with drive-by-wire (DBW) controls, effectively and efficiently to train subjects in a variety of ways. A DBW system utilizes electrical circuits to actuate servo motors from a given input signal to achieve a desired output. In DBW systems the output is not directly mechanically connected to a control surface (steering, acceleration, deceleration, etc.); usually, the input controller is linked by electrical wires to a localized servo motor where direct control can be given.

This project is aimed at developing a novel simulator for a future training program using DBW systems that caters specifically to individuals who currently use or will be using for the first time vehicle modifications in order to drive and maintain their independence. Many of these individuals use one or a combination of powered steering, acceleration, braking, or secondary DBW controls to drive. The simulator integrates a virtual training environment and advanced electronic vehicle interface technology (AEVIT) DBW controls (4-way joystick, gas-brake lever/small zero-effort steering wheel).

In a 30 participant study of three groups (able-bodied individuals, elderly individuals, and individuals with disability), it was found that training with a DBW joystick steering system will require more instruction and simulator practice time than a gas-brake lever/small steering wheel combination (GB/S) to obtain a similar level of competency. Drivers using the joystick completed predetermined driving courses in longer times, at slower speeds, with more errors than the other DBW system. On average, the reaction time to a stopping signal was fastest with the gas-brake lever at 0.54 seconds. Reaction times for the standard vehicle controls and the joystick were 0.741 and 0.677 seconds respectively. It was noted that reaction times using DBW controls were shorter overall. When driving in traffic, drivers committed 4.9, 5.1, and 8.3 driving infractions per minute using standard vehicle controls (No Drive by Wire, (NDBW)), the gas/brake and steering system, and joystick system respectively. Most drivers felt that the GB/S system was easier to learn, easier to operate, safer, and more reliable than the joystick system.

Chapter 1: Overview

1.1 Motivation

It is commonly known that one of the aspects of an individual's freedom lies in their ability to drive. In fact, it is a necessity, being the primary means for going to the store to get groceries, participating in social activities, and maintaining a sense of independence. Most take the privilege of driving for granted and do not think twice about how they might get around without a vehicle. However, certain individuals with disabilities, particularly those who suffer from a degree of paralysis cannot drive without some form of vehicle modification. For the paraplegic who has full upper mobility, a vehicle must be modified so that acceleration and braking controls can be utilized by the hands. On the other hand, a quadriplegic, who only has limited mobility in their hands, requires more extensive vehicle modifications in order to drive.

Once an individual with a disability does have a vehicle fitted with adaptive controls, they must undergo training in order to obtain a new license. This training is organized and conducted by state-run Vocational Rehab agencies. Drivers, in the presence of an evaluator, practice on-road with their new adaptive equipment in order to learn the necessary skills to proficiently drive. The problem is that this instruction is not always on a closed course; rather, it is given in parking lots and less frequently used roads where the possibility that traffic will be encountered does exist. In the event that training is conducted on a closed circuit, it is still not entirely a completely controlled environment. There is still a danger that a new driver may lose control of the vehicle while using unfamiliar controls and have an accident.

The solution to this problem is to develop a training environment that is safe, controlled, and easy to access for those who might require it. A driving simulator can offer all of these aspects. At the same time, it can be tailored to meet each individual's unique needs. A number of studies have developed driving simulators that can be used for rehabilitation and training for stroke victims who use either the right or left side of their body for control. However, to the best of this author's knowledge, all have excluded individuals who require Drive-By-Wire (DBW) controls to maintain their driving independence. DBW controls electronically link input and output devices in vehicles whereas mechanical controls link interfaces to terminal devices. In most cases, the studies require that individuals to have the ability to use both hands and feet.

The thesis topics include the background and history of simulation technology, simulator use for therapy and training purposes, assistive devices for vehicles, DBW simulator design, a participant study, results, conclusions, and ideas for future work. Chapter 2 gives the reader an overview of simulator technology and describes the current state-of-the-art. Chapter 3 describes the need for simulators for safe training while outlining the limitations of recent studies. Chapter 4 includes an overview of assistive devices (primary and secondary controls, orthotic devices, lift, etc.) that persons with disability commonly use during driving tasks. Chapters 5 and 6 detail the integration of DBW systems and a standard driver training simulator and an investigation of performance of individuals using the setup, including testing methods. Chapters 7 and 8 discuss the results of the human-subject tests and the conclusions that can be drawn from the data. Furthermore, chapter 9 elaborates on how the simulator can be enhanced to facilitate the development an effective training program. Ideas for future research are also mentioned.

1.2 Research Objective

As previously mentioned, there are currently no driving simulators with DBW controls in use for training individuals with disabilities or for the elderly population. The objective of this thesis is to develop the framework for a novel driver training simulator that can be easily utilized to meet the needs of those individuals and develop the state-of-the-art of the vehicle modification and training industry.

This new idea for an integrated DBW simulator will give persons with disabilities the necessary extensive training before actually using the roadways and reduce the cost of their training. Vehicle modifications encompass a vast number of different controls and adaptations including mechanical and electromechanical controls. This study does not include the integration of adaptive mechanical controls. Mechanical controls in this study are limited to the standard gas and brake pedals, and steering wheel found on all vehicles. Adaptive equipment is limited to DBW controls (4-way joystick, gas-brake lever/small zero-effort steering wheel) and some attached orthotic devices.

This paper will seek to address the current issues related to vehicle modifications and DBW controls. Furthermore the following questions are to be studied after human subject testing of 30 individuals:

1. What are the differences in performance among different user groups?
2. What are the differences in performance among different driving systems?
3. What is the difference in the learning curve among groups?
4. Is there a difference in safe driving practices using DBW controls versus standard equipment?
5. How do users perceive the use of the adaptive driving systems?
6. In what areas can adaptive driving equipment help those without a disability or the elderly?

The objectives include:

1. Set up a working virtual reality simulator with DBW controls (AEVIT joystick, AEVIT gas/brake lever with small steering wheel)
2. Test the systems
3. Conduct a participant study
4. Determine relationships and trends

Chapter 2: Background

The Air Force trains pilots to deal with aircraft malfunctions, vehicle control, and combat situations before placing them in multi-million dollar aircraft. Navy officers are trained to maneuver large vessels safely and NASA astronauts practice missions and procedures to perfection all without the risk of human safety or equipment damage. It is evident that any number of these activities would be impractical and unsafe to practice in a real environment.

2.1 History of Simulators

The use of simulators dates back to the early 20th century as a direct result of the Wright brothers' ingenuity and innovation in aeronautics. In 1929, the cost of flying was relatively high and out of the reach of most Americans. Edwin Albert Link (Figure 2.1) a young man with a burning desire to fly was one of these Americans who did not have the financial means to fly. For a year and a half, he worked on the development of a simulator that would emulate the sense of flying.

Figure 2.1 - Albert E. Link, Simulator Pioneer [1]

Albert finally built the *Link Trainer* (Figure 2.2) which is often referred to as the *Blue Box.* Being an organ maker by trade, he had extensive knowledge of pumps and was able to implement working dials and gauges in his design. The *Trainer* looked like a miniature version of an aircraft, having short, stubby wings and a fuselage large enough for a grown man to sit in. The fuselage was mounted via a universal joint which allows for the simulation of pitch and roll. Each axis was independently adjustable; the model could be lifted and lowered via a bellows system similar to those found in organs [2]. The *Link Trainer* bellows movement was driven by an electric pump that was coordinated with the pilot's input from the controls (Figure 2.3). The design was awarded a patent in 1934 [3].

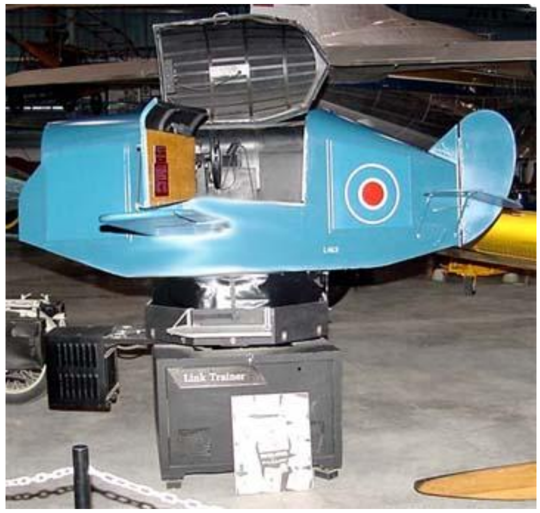


Figure 2.2 - Link Trainer Sometimes Called the "Blue Box" [4]

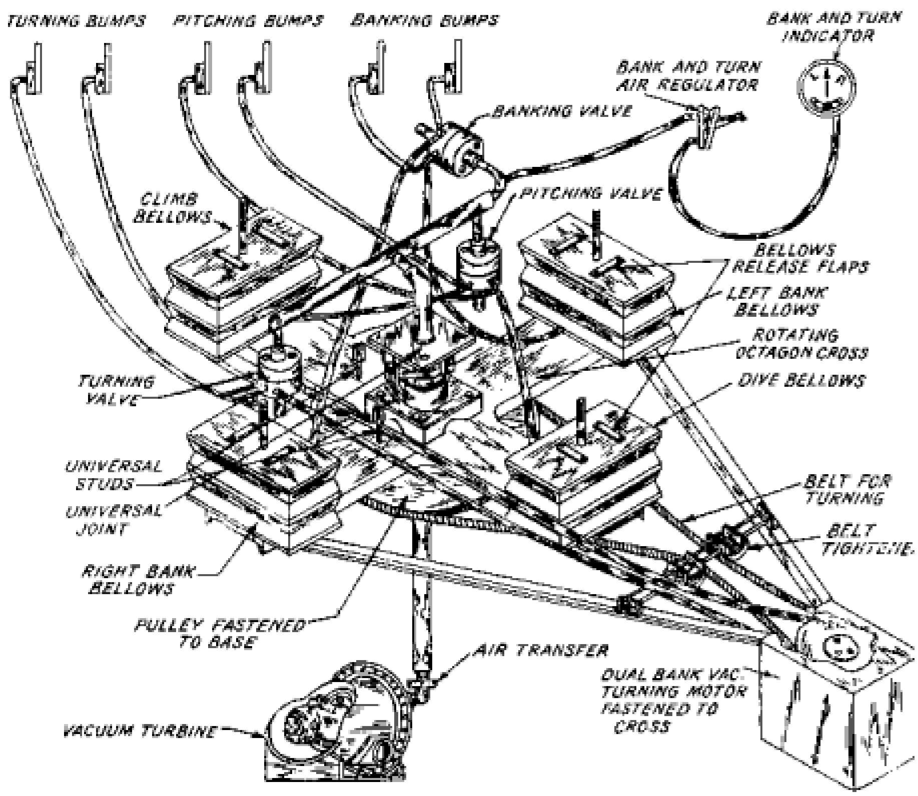


Figure 2.3 - Bellows System in the Base Platform of a *Link Trainer* [5]

While the first *Blue Box* trainers were built and sold as amusement rides for parks, the United States military, realizing the training potential of Link's trainer, gained interest, and purchased six for a price of $3500 each in 1934 [1]. The Army Air Corps intended to use the simulators to train their pilots to fly in hazardous conditions (night, flog, etc.). Subsequently, thousands of units were produced and used by over half a million airmen in countries around the globe and by the end of World War II, nearly every pilot from every branch of the military had logged some time in a *Link Trainer* [3].

Although Link's trainer paved the way for today's advanced high-fidelity simulators, it only simulated the sensation of motion accompanied with realistic controls and working gauges. In order to effectively train individuals in a simulator, the environment must be able simulate a variety of configurations, something the *Link* trainer could not easily do. While some models had an opaque canopy for simulating night flight navigation via instrumentation only, it was unable to visually simulate rain, snow, or other inclement weather condition. This was not available until the integration of virtual reality in simulators.

2.2 History of Virtual Reality

The idea that virtual data could be output on a display screen, such that information could be easily seen and comprehended by a viewer, was first proposed by a Navy radar technician and electrical engineer by the name of Douglas Engelbart (Figure 2.4). Before his ideas, and the subsequent invention of a graphical user interface (GUI), large room-sized computers delivered data via strings of numbers in an enigmatic language that was only readable by those well versed in programming. Engelbart hypothesized that if a person could interact and manipulate computers, it would change the way people viewed and used them. Indeed, he was right.

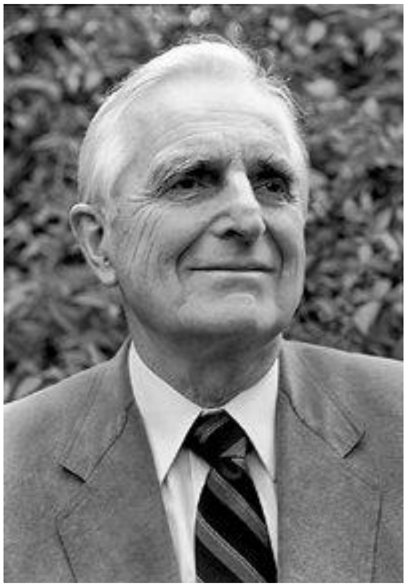


Figure 2.4 - Douglas Engelbart [6]

Virtual simulators, essentially, are simply graphical user interfaces that incorporate a means of modifying the virtual environment 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 (Figure 2.5). 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 the 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 advanced controllers and interfaces that are used today [8].

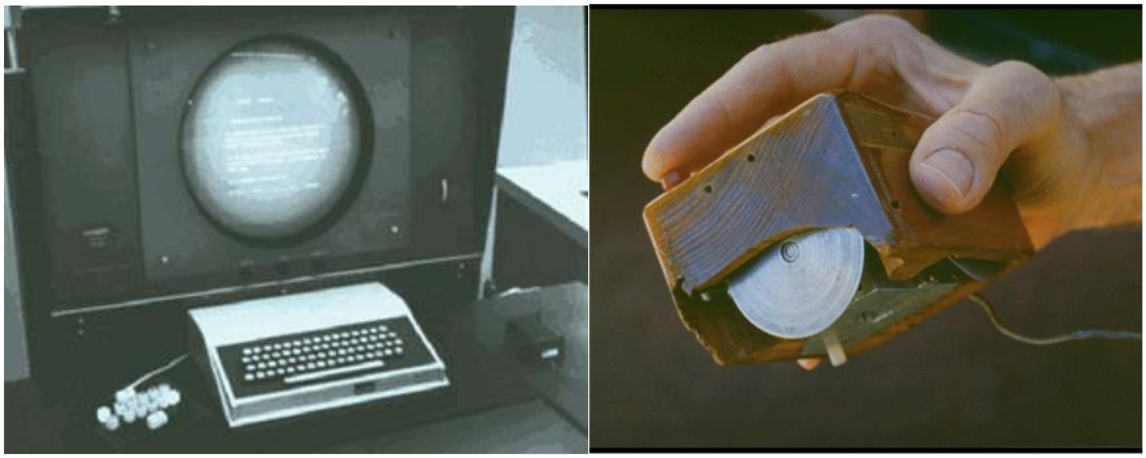


Figure 2.5 - Engelbart's Contribution to Virtual Reality, the GUI [7] and the Mouse [8]

2.3 Enhanced Presence in Simulators

Today’s virtual simulators incorporate aspects from both Engelbart and Link’s research. The combination of a dynamic platform and a graphical user interface used in conjunction with a manipulative controller give subjects an enhanced presence in simulators. The goal of simulator design is to make the unreal environment seem as if it was real. In order for enhanced presence in a virtual environment (VE) to occur, two aspects must exist: involvement and immersion [9].

Witmer and Singer define involvement as the degree in which a person focuses on a given task. Focus can be divided by a preoccupation with other thoughts and distractions. However, as a user of a VE focuses on the stimuli of the simulator, their involvement increases. This is affected by the ability of the virtual environment to capture and hold the subject’s attention [9]. One example of a virtual environment that has a high degree of involvement is a video game. The game is entertaining, interesting, and often includes some sort of plot that encourages the user to maintain focus so that one can advance in the game.

Secondly, there must be immersion. According to Witmer and Singer, the video game gives a high degree of involvement but does little to immerse the user in the environment. Effective immersion can be achieved by removing a user's ability to gather sensory data from the surrounding environment. Many simulators often are in enclosed spaces. This effectively forces the user to get a sense of presence from the virtual environment only. A person who is ideally immersed in a virtual environment will feel as if they are moving with the simulated environment and not apart from it [9]. Table 2-1 lists and briefly describes factors influencing enhanced presence.

Table 2.1 - Factors Affecting Enhanced Presence [9]

Control Factors	· Degree of control · Immediacy of control · Anticipation of events · Mode of control · Physical environment modifiability
Sensory Factors	· Sensory modality · Environmental richness · Multimodal presentation · Consistency of multimodal presentation · Degree of movement perception · Active search
Realism Factors	· Scene realism · Information consistency with objective world · Meaningfulness of experience · Separation anxiety/disorientation
Distraction Factors	· Isolation · Selective attention · Interface awareness

One of the earliest known simulators to integrate immersion and involvement to obtain presence was developed by Morton Heilig in 1956. The simulator had a short 10-minute video (visual) of a motorcycle ride through New York city in which users were subjected to urban smells (olfactory), traffic noises (auditory) and vibrations (tactile) from the seat on which they sat [10]. This technique is called multimodal presentation (affecting multiple senses) and is one of the sensory factors proposed by Witmer and Singer. Despite the multimodal presentation, the *Sensorama* (Figure 2.6) does not allow the user to interact with the environment.

Figure 2.6 - Heilig's Sensorama [10]

2.4 Current Research

2.4.1 Dynamic Traffic Behavior

Furthermore, enhanced presence is increased by scene realism. In driving simulators, a dynamic traffic program allows users to experience real world driving scenarios in that ambient traffic behaves very similarly to the real world, thus, increasing scene realism. Recent research by Wright (University of Leeds), Leeds (University of Minnesota), and Cohn (University of Leeds) argues that for simulators to be most effective, an "enhanced sense of presence" must be developed. This can be attained by implementing autonomous traffic with varying personalities. Their hypothesis was backed by a participant study that concluded that a more natural traffic behavior contributes significantly to the realism of driving within a virtual environment. Since driving simulators are being used more often for safely training, testing in vehicle systems, and evaluation of driver behavior, there is a need for enhanced realism in order for results to be valid and relevant to real world scenarios.

Currently, autonomous vehicle traffic is made of two parts: ambient and event driven. Event driven traffic is designed to react to a specific scenario introduced by the user. For instance, if a person approaches a stop sign at an intersection, another vehicle might run the stop sign and force the user to react to avoid a collision. Secondly, the ambient traffic serves to disguise event driven vehicle and create the feeling of a busy roadway. A driving experience is directly enhanced by a better ambient traffic behavior [13]

2.4.2 National Advanced Driving Simulator

The University of Iowa is currently home to one of the world's most sophisticated and immersive driving simulators. The National Advanced Driving Simulator (NASD) (Figure 2.7), funded by the National Highway Traffic and Safety Administration, integrates a significant portion of Witmer and Singer's contributing factors for enhanced presence in that it can provide very realistic motion in the virtual environment while delivering high-fidelity sounds in a vehicle cabin among other features.

Figure 2.7 - National Advanced Driving Simulator [11]

The NASD-1 has 13 degrees of freedom and can reproduce accelerations similar to those experienced in the real world under a variety of scenarios. During turning and stopping tasks, drivers experience the greatest forces due to change in velocity. The NADS-1 is capable of delivering the motions that simulate these resulting accelerations. Moreover, the 360-degree view further immerses the subject in the virtual environment and makes training for lane changing and checking of blind spots possible. The NADS-1 is able to accept a number of different vehicle designs; a variety of full-size vehicle shells can be inserted into the simulator. Trucks and cars respond to user inputs differently and therefore require differing responses from the simulator for an accurate simulated control response. This is achievable by the flexibility of a programmable response curve for each type of vehicle [11].

2.4.3 Low-Cost Mechanical Driving Simulator

The NADS simulator is highly effective in that it gives users enhanced presence. However, its equipment that provides its high-fidelity is extremely expensive. At the same time, a large facility is required to house the simulator. The cost prevents it from being produced in any quantity and therefore limits public access for training. This is the case with most modern dynamic simulators and the reason that static simulators are much more common despite being much less effective. All simulators that are mounted to a dynamic platform utilize the same basic concept. By adjusting the pitch or roll in any direction, the sensation of movement is created. This sensation is detected in the vestibular system in the human body and by one's detected sense of motion from visual cues. In simulators, the same feeling of movement can be achieved by tilting a seat so that the acceleration due to gravity creates the sense of change in velocity assuming that the rotation rate of tilt is low. Even though the motion is rotational, the human body feels as if there is translational motion, especially if a simulated virtual environment shows translational motion while blocking all external references. The limitation is that acceleration equal to gravity is the maximum achievable by this technique. Acceleration higher than gravity can be established only by a translational acceleration.

This method was implemented by researchers at the Politecnico de Milano in Milano, Italy. Their goal was to create a low-cost dynamic driving simulator (Figure 2.8) so that rehabilitation centers and other training sites could afford to have a realistic ground vehicle driving simulator. The simulator has four degrees of freedom (rotation about x, y, z and translation in x). The simulator is mounted on a track and can be accelerated so that acceleration higher than gravity in ‘x’ is possible. Additionally, simulated translation along the x-axis (forward/rearward) is obtained by small rotations about the y-axis. In contrast, simulated translation along the y-axis (left/right) is simulated by rotation about the x-axis. Simulated translation in the z-axis (vertical) is impossible since acceleration due to gravity already at a maximum. Their results showed that perceived translations in x and y are possible but z is more difficult to obtain [12].

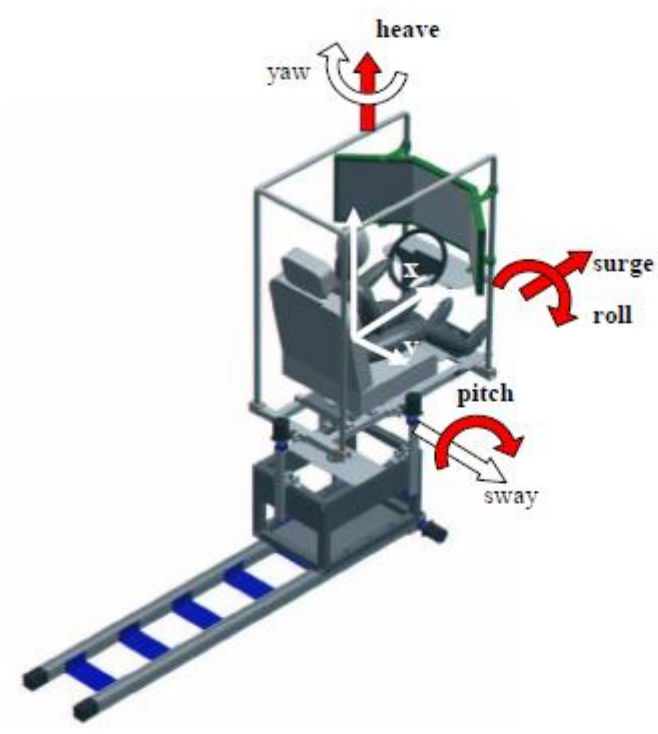


Figure 2.8 - Low-cost Simulator [12]

Chapter 3: Simulators Used for Therapy and Training

Simulators have long been implemented for training and have more recently for therapy. The military trains pilots and war fighters using simulators for tasks that might be very dangerous, expensive or impossible in the real world. For example, a pilot could be trained to deal safely with the loss of propulsive power in a virtual environment. In an actual aircraft, the test could potentially be life-endangering. Furthermore, a solider could be trained to escape a vehicle after roll-over under varying conditions while his performance is recorded (Figure 3.1).

Figure 3.1 - Army Humvee Roll-Over Simulator [14]

After training, the results can be used to further education. The United States is aware of cases in which this type of repetitive simulated muscle-memory training has saved lives [15].

3.1 Review of Simulator Based Therapy

Inherently, driving simulators are effective and useful tools for training individuals. They model driving behavior and performance. Naturally, they are being used for stroke victims. Researchers at Stanford University have researched methods of therapy for persons who suffer from brain damage from stroke using driving simulators for steering tasks. Before their work, the intent of simulator design was to determine how the use of drugs and alcohol impaired driving ability and decision making. Their split-wheel design studies the limitations of individuals with impaired upper mobility as a result of head injury or stroke and supports the use of simulators for therapy.

By adding simple task to a driving scene, in addition to sensory feedback (auditory, touch, and visual) the simulator can effectively determine a person's ability to steer a vehicle. The simulator is called the Driver's Simulation Environment for Arm Therapy (SEAT) (Figure 3.2). The steering wheel consists of a direct-drive motor attached to a split steering wheel and an assortment of force sensors. This allows the researchers to determine how a subject uses both arms in steering wheel control. Persons with upper arm limitations, particularly stroke victims, will use the unaffected arm to both pull and push the steering wheel. This habit can be monitored with the use of the SEAT because the steering split steering wheel was capable of measuring forces on each side.

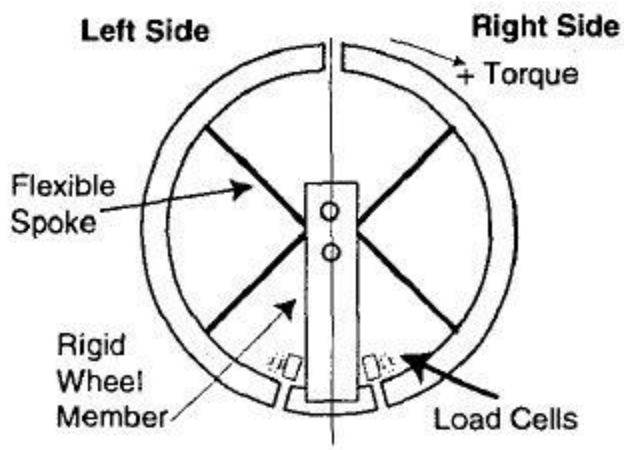


Figure 3.2 - Split Wheel Design [16]

For testing, vehicle speed remained at a fixed constant, which eliminated the need for the subject to have to control acceleration and braking. In the same way a steering wheel controls lane position of a vehicle, the SEAT controlled the lateral position of the vehicle in the virtual environment. Subjects were asked to sit in a wheelchair with their hands at the 2 and 10 o'clock positions on the steering wheel. A steering task designed to encourage the use of the impaired limb was given to the participants. Their results document an increased use of the affected limb during the bimanual task [16].

3.2 Transfer of Training

Training in simulators has several obvious advantages over training in the real world, but it is also important to note that there can be some negative aspects as well. One of the most important aspects of driving simulators is the effectiveness of the transfer of training. Both cognitive and motor tasks can have "positive" or "negative" transfer of training. Positive transfer of training occurs when simulator training results in the positive improvement in the real world scenario. On the other hand, negative training occurs when performance is degraded as a result of the simulator training.

Simulators have proven their validity in the past simply because they are safer, cheaper, and can train users for simple tasks where the environment and parameters of the task can easily be controlled. Benjamin Bollmann and Lukas Friedrich, of ETH Zurich, Switzerland, developed a series of tests to determine how training in a VE affected performance in the real world. Three groups with different levels of training were established: no training, real world training, and VE training. Study participants were asked to complete three tasks to test their motor skills and one to understand the usefulness of simulator training for cognitive tasks.

Their results varied widely from one group to the other, however, those who were trained in a VE and in the real world, performed better than those who received no training at all. This result was expected. However, it was also noted that, if the subject was given some sort of distracting interference during a motor-skills oriented task in the real world, those who trained in the virtual environment performed better than those with real world training. The researchers concluded that this was due to the fact that VE trainees had to develop their motor skills without the benefit from any form of haptic feedback. Therefore, their increased performance was directly related to muscle-memory without any sensory. Their cognitive ability was free to deal with the interference. Furthermore, since the virtual environment does not have haptic feedback it becomes more difficult to accurately complete tasks, and the training model becomes more effective [17].

These findings are important and relevant to driving simulator training in that often drivers in the real world experience a significant number of distractions even over short durations. A driver might have passengers who are talking, make adjustments to the radio or climate controls, or even answer telephone calls. These all represent major distractions and take away from the driver's cognitive ability to react to other distractions and to continue driving safely.

3.3 Evaluation of Driving Performance

One of the current limitations of training in driving simulators is that there is not a standard for evaluation of driver performance. Presently, a driver must test at a local branch of the Department of Motor Vehicles with an evaluator. The driving privilege allows individuals to maintain their independence and is critical in order to have a sense of self-sufficiency.

Often times, those who have a traumatic brain injury or an acquired brain injury are limited and even precluded from rejoining the workforce because their license must be reinstated before legally being able to drive again. In order for individuals who have brain injury to regain their driving freedom, they are subjected to qualitative tests behind the wheel of a vehicle. The use of a virtual reality driving simulator would provide an objective and qualitative assessment of driving capability [18].

A recent study uses driving performance related to a stopping (stop sign) task in a simulator to compare the performance of adult drivers who do and do not have a brain injury. They found that a virtual reality simulator can, in fact, be used to determine an acceptable set of objective qualifications to evaluate the driving ability of a person with an acquired brain injury.

Before this research study, most driving research was aimed the evaluation of healthy individuals. The same is true for research on driving accidents. There is a scarcity of research on the accident and circumstances related to those accidents involving persons with disabilities, particularly those with acquired brain injury. These studies are necessary because they are the basis that governing bodies use to modify and ratify new traffic laws to promote safety and minimize deaths [18].

Furthermore, The U.S. Department of Transportation studied the causes of fatal traffic crashed and determined that the likelihood of being involved in a fatal traffic accident at an intersection controlled by a stop sign is 2.5 times as likely than at an intersection controlled by a light [19]. On the other hand, there have been no studies on the driving violations and traffic accidents caused by those with brain injury.

A person driving uses a complex integration of the senses to safely maneuver. However, this can be difficult for those who have an acquired brain injury. The clinical tools used to determine one's ability to drive are flawed in that they are not standardized or subjective. Virtual reality simulators eliminate these errors by providing a realistic driving scene removed from subjectivity and enhanced by the ability to repeatedly assign tasks in a safe environment.

In the study, performance is determined by vehicle speed, lane use, traffic signal response, and a few other parameters [18]. The specific task studied related to stopping at an intersection which was controlled by a stop sign. Fifteen persons with acquired brain injuries were compared against 9 healthy individual control subjects. The persons with disability and the healthy controls were matched on the basis of driving experience and age. *The study did not, however, include persons who required the use of assistive driving devices.*

Their virtual reality driving simulator consists of a software and hardware portion. Steering is controlled by a steering wheel and a gas/brake foot pedal. The virtual environment is displayed on a desktop computer display. The system integrates forced feedback to make the experience more realistic. The software was custom designed and included situations that a driver might encounter on a regular basis within the real driving world. The simulated route is approximately 1-mile long and included a number of stop signs. For every .2 second interval, data was collected on the speed, deviation from the center of the lane, distance to stop sign, and turn angle. The stopping zone in which data was analyzed was plus and minus 25 feet of the stop sign. This zone is established by the DMV in NJ and NY. During the task a driver stopped fully if their vehicle speed reached 0 mph. They also were evaluated by the amount of time that they spent, fully stopped at the sign, and by approaching and departing speeds. Overall, those with acquired brain injury were more likely to not stop, stop over a longer distance, and remain stopped at the sign for shorter lengths of time. Approaching and departing speeds were similar to the healthy controls' data.

Nevertheless, both of the groups were able to show a marked pattern of improvement from repeated exposure to the tests. This shows that the simulator can be used as an effective tool for rehabilitation and the consequent need for an evaluative standard. Great gains were shown over a relatively short period of time. The sample size was too small to justify establishing guidelines for driving rehabilitation and clinical validity of using virtual simulators for training, but shows the need for improved research on the topic [19]. The information from this study is helpful for the creation of driver simulator training program for this study despite the lack of concrete guidelines.

Chapter 4: Assistive Devices in Vehicles

Persons with a disability often times require some sort of vehicle modification or installation of adaptive equipment. This may include the installation of ramps, lowered floors, transmission controls for gear selection, hand or foot controls, or even voice activated controls. Depending on the degree of the disability, extensive changes may be necessary. It is somewhat common for powered wheelchair users to have lowered floors in their vehicles. Someone with diabetes may only need a form of mechanical hand controls due to their lack of sensation in lower limbs as a result of poor circulation. Whatever the need is, drivers with disabilities require evaluation by a state-appointed driver rehabilitation specialist. The specialist determines a person's individual needs based on both physical and cognitive ability and writes a prescription for the necessary equipment and vehicle modifications [20].

Once a vehicle has been properly modified by a certified National Mobility Equipment Dealers Association (NMEDA) business, the driver must essentially go through a basic driver training course with the driver rehabilitation specialist [20]. This training is organized by the each state's Department of Motor Vehicles. Unfortunately, these vehicle modifications and the subsequent training are rather costly.

4.1 Types of Chairs and Securements

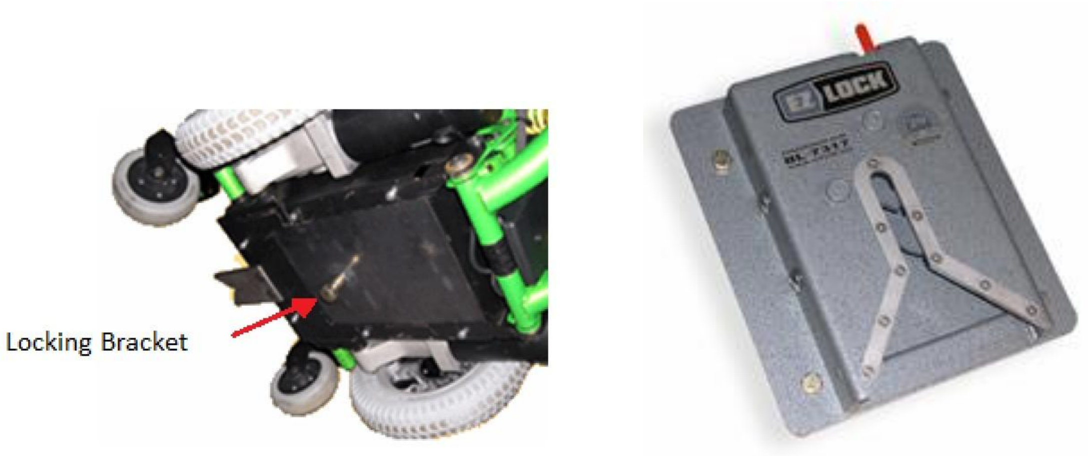
Many individuals who have a disability use a wheelchair to maintain their independence. Wheelchair design is broad category including many types and styles. Figure 4.1 shows a few: manual chairs (a), powered wheelchairs (b), specialized chairs for athletic activities (c), and scooters (d). Chairs typically include a form of securement device so that the chair can be safely locked in place in a vehicle.

(a) (b)

(c) (d)

Figure 4.1 – Types of Wheelchairs [22], [23]

In fact, the American Disabilities Act has several requirements for modified vans and public transportation vehicle. All vehicles regardless of size must have at least one two-part device for securing chairs; one device must secure the chair while a shoulder and lap belt must secure the user. Vehicles over 22 feet in length must have at least two of these systems [21].



(a) (b)

Figure 4.2 - EZ Lock Securement System [24]

(a) Locking bracket on bottom of powered chair, (b) EZ Lock docking base

Figure 4.3 - Anchoring Strap [25]

The EZ lock system (Figure 4.2) is a very convenient method for securing individuals' chairs. The device is commonly installed in personal vehicles and it is only necessary for a person to drive the wheelchair into the base. This motion causes the base to latch onto the bracket and lock the chair in place. Some models can be unlatched remotely via an electronic switch. There is also a cable operated backup system. This system is more costly than the strapping method seen in Figure 4.3. In contrast, a second party must secure the chair for the individual, making it less convenient. In order for the chair to properly be secured, more than one strap must be implemented.

In an effort to ensure safety for vehicle occupants the Americans with Disabilities Act requires that [25]:

1. The vehicle floor space provided for a wheelchair be at least 30” by 48” (this is the defined maximum allowable size for a “standard wheelchair).
2. The occupant must be secured so that he or she is forward or rearward facing.
3. Each securement (EZ Lock, strap, etc.) must be capable of withstanding a tensile force of at least 2,500 lbs so that the chair does not move more than 2” in the event of a collision.
4. A lap and shoulder belt must be available for the rider to wear.

4.2 Vehicle Modifications, Ramps, and Lifts

In some cases, drivers who use manual chairs and have a high degree of mobility can transfer into a vehicle and then load the chair into the seat behind. Others, especially those using heavy chairs require lifts and/or lowered floors. Minivans are the most popular vehicle for modification. They are smaller than full-sized vans but are still large enough for an individual to drive a wheelchair into while seated therein. Minivans need to be equipped with a lowered floor. This allows a user to easily drive a chair into the van via a side-opening ramp (Figure 4.4) without hitting his or her head on the ceiling.

Middle seats are removed to allow for extra room. Rear access ramps are also available but these are more suited for wheelchair-bound passengers. One disadvantage of a lowered minivan floor is that a driver must take extra care on uneven surfaces. Speed bumps are common causes of damage. If a person with a disability chooses to modify a full-sized van lift is necessary as the floor height is too high for a ramp. Side lifts and ramps require extra room in a parking space. Additionally, lifts and powered ramps can be operated by one person [26].

(a) (b)

Figure 4.4 Vehicle Modifications

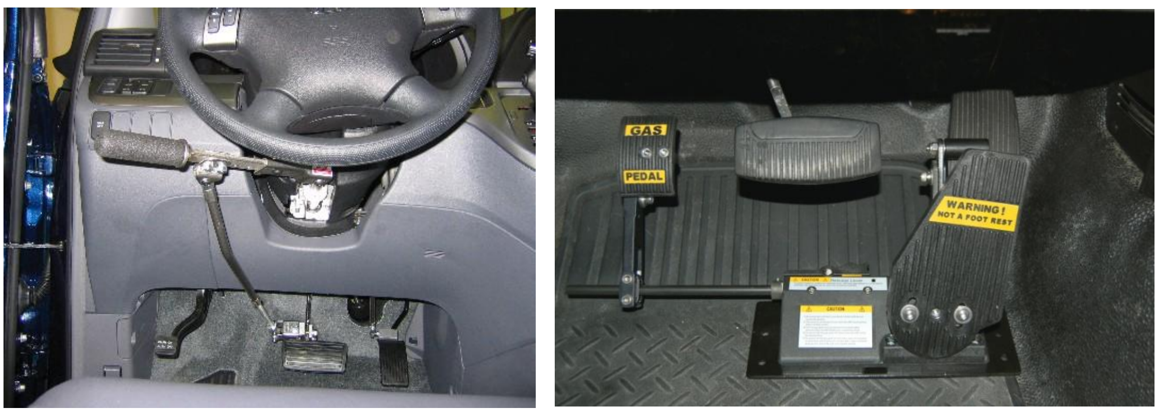
(a) Minivan with a ramp and lowered floor [28], (b) Van equipped with a lift [29]

4.3 Primary Controls

Primary controls consist of two major categories: mechanical and drive-by wire. Mechanical controls typically cost less than $1000 dollars whereas advanced electronic control systems can cost as much as 70 times that. The nature of primary controls is to allow a driver with a disability to effect the gas or brake and steering wheel. Primary controls may be implemented in one controller (gas-brake/steering) or can be split into two separate controllers (gas-brake and steering).

4.3.1 Mechanical Controls

Mechanical controls are usually cost-effective solutions for individuals who have paraplegia or full upper mobility. According to the National Mobility Equipment Dealers Association, there are four types of hand controls for acceleration and braking (push-pull, twist-push, push-rock, and right angle-push). Mechanical controls are advantageous in that they do not interfere with an able bodied person's ability to drive the vehicle. Pedal extensions and portable controls (used for rental cars by users with good upper-body strength) are some other forms of primary mechanical controls [30]. Figure 4.5 shows some examples of mechanical controls.



(a) **(b)**

Figure 4.5 – Examples of Mechanical Controls

(a) Right angle push acceleration-braking control [31], (b) Left-foot accelerator control [32]

4.3.2 Drive-by-Wire Controls

Drive-by-wire controls are far more expensive than mechanical controls and are only installed in a vehicle when absolutely necessary. This type of equipment is best suited for individuals with tetraplesia or extremely limited mobility in all limbs. A drive-by-wire device or electronic control uses electrical power produced by the vehicle to affect an actuator such as a servo and give a desired motion based on the user's input. Typically, the control reduces the necessary input force by approximately 40% or 70%; it is termed as a "reduced-effort" or "zero-effort" device in the mobility equipment industry. Furthermore, necessary length of travel for full operation is generally reduced to a few inches [33].

The majority of drivers using electronic controls have the ability to use both arms for vehicle control. Depending on the user's preference, one hand will control the steering controller while the other will operate a gas-brake controller. Gas and brake control is typically a lever-type interface in which the operator pushes in one direction for acceleration and the other for braking. Steering can be accomplished via a remotely located miniature steering wheel. In the event that a driver does not have full use of both arms, the two separate controls can be integrated into one. Currently there are two styles of one handed control; the tri-pin or joystick one handed driving system (Figure 4.6) [33].

Figure 4.6 – Type of One Handed Steering Device [34]

4.4 Secondary Controls

Adaptive equipment not related to accelerating, braking, or steering the vehicle is considered a secondary control. Some secondary controls are absolutely necessary for the proper function of the vehicle while other operate vehicle accessories. These include: remote transmission shifting units, EZ Lock disengagement controls, climate control, remote ignition, airbag switch, interior and exterior lights, powered parking brakes, signaling devices, horn, etc. [30]. Some mobility equipment dealers offer integrated control interfaces in the form of a button-activated or touch screen display (Figure 4.7).

Figure 4.7 – AEVIT Secondary Control Unit [35]

4.5 Orthotic Devices

Some individuals are unable to safely utilize adaptive equipment without a specialized attachment. For this reason mobility equipment dealers offer several types of orthotic attachments to suit a variety of needs. Often times, a user lacks manual dexterity and is unable to firmly and securely grasp the control. In this case, a tri-pin attachment can be installed. It allows an individual to maintain constant control of the steering or acceleration controller. Extension levers, loops, straps, T-handles, knobs, and splints are also commonly used [36] (Figure 4.8).

Figure 4.8 – Some Electronic Mobility Controls Orthotic Attachments [36]

Chapter 5: DBW Simulator Design

A person learning a new skill set requires adequate training and instruction in order to master the task and develop pertinent motor skills. The same is true for individuals with newly modified vehicles using adaptive equipment. Simulators offer a safe means of providing this training. Not only is it advantageous in that the risk associated with driving in a virtual environment is essentially removed, but, it provides a means of low-cost training as the cost of training with vehicle modification evaluators is very high.

This project is aimed at studying how a simulator can be used for training individuals with disabilities. Typically, persons with a limited range of motion in their hands and feet use electronic or drive-by wire (DBW) controls. They will benefit the most from this simulator. It will allow users to practice safe vehicle control and become proficient drivers before undergoing evaluation with their newly modified vehicles. Since drivers with disabilities have few resources of training safely in their vehicles before using public roadways and parking lots, this is a necessary and important tool.

The simulator consists of two major components: the SSI (Simulator Systems International) simulator and the AEVIT (Advanced Electronic Vehicle Interface Technology by Electronic Mobility Controls) DBW control system. The SSI simulator displays the virtual driving environment. Secondly, the AEVIT system is equipped with two separate input controller systems: a 4-way joystick and a small steering wheel/gas-brake lever. The signals from the controllers are processed in an input drive module and the signal is then read by a servo motor controller. The steering servo is mechanically linked by a gear set to the original integrated steering column on the SSI simulator unit. The gas/brake pedals are connected to the servo motor through a series of steel cables.

5.1 SSI Simulator

The SSI simulator is essentially a Windows-based computer that has been built around a steering wheel and column (Figure 5.1). A number of the basic functions on a car's dash are present, including headlights, keyed ignition, shift lever, overdrive switch, emergency flashers, windshield wipers, horn, and high beams. Additionally, there are some auxiliary switches. Two lit switches can be activated to indicate to the computer that the seat belt is fastened and the hand brake is applied. The simulator model used in this project was equipped with only one view screen. In order for a driver to look to the left or right of the windshield or to check right or left blind spots, an associated switch must be flipped and held.

Figure 5.1 - SSI Modular Driving Simulator [37]

Springs attached to the steering shaft return the steering wheel to center position whenever a driver releases it. This models a real car that is in motion. However, if a driver is stopped in the virtual environment, the wheel unrealistically has a tendency to return to center. Acceleration and braking controls are used with the simulator to control acceleration and braking. The pedals are mounted on a weighted base. At rest the pedals are at 65 degrees. They are at a 35 degree angle when fully depressed (Figure 5.2). These angles are comparable to real vehicles. There is an option for a third pedal for clutch. It is not used for this project.

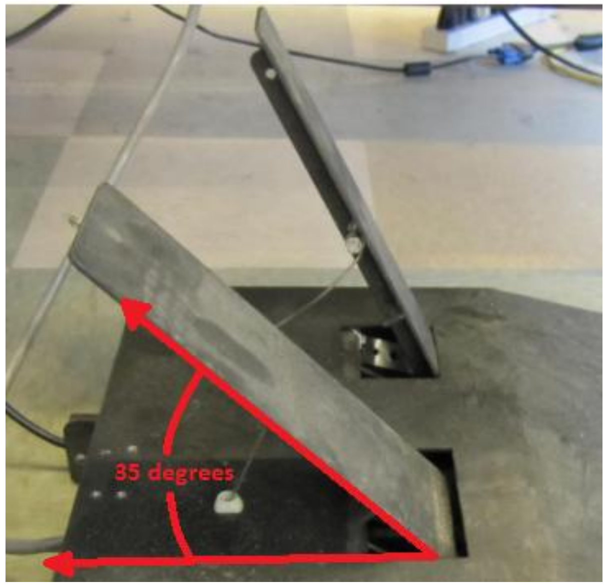


Figure 5.2 - Range of Motion of Pedals

5.2 AEVIT Control System

The AEVIT (Advanced Electronic Vehicle Interface Technology) system is a servomotor control system developed by EMC (Electronic Mobility Controls). A single servomotor controls both the gas and brake functions while another separate servomotor controls steering functions. The system is modular in that the controller drive module is capable of accepting a variety of controllers. Therefore, the same basic hardware can be used to interface with a joystick, lever, small steering wheel, etc.. The controls are equipped with redundant potentiometers so that controller and servo position can be checked for errors for safety. Figure 5.3 shows the general system layout.

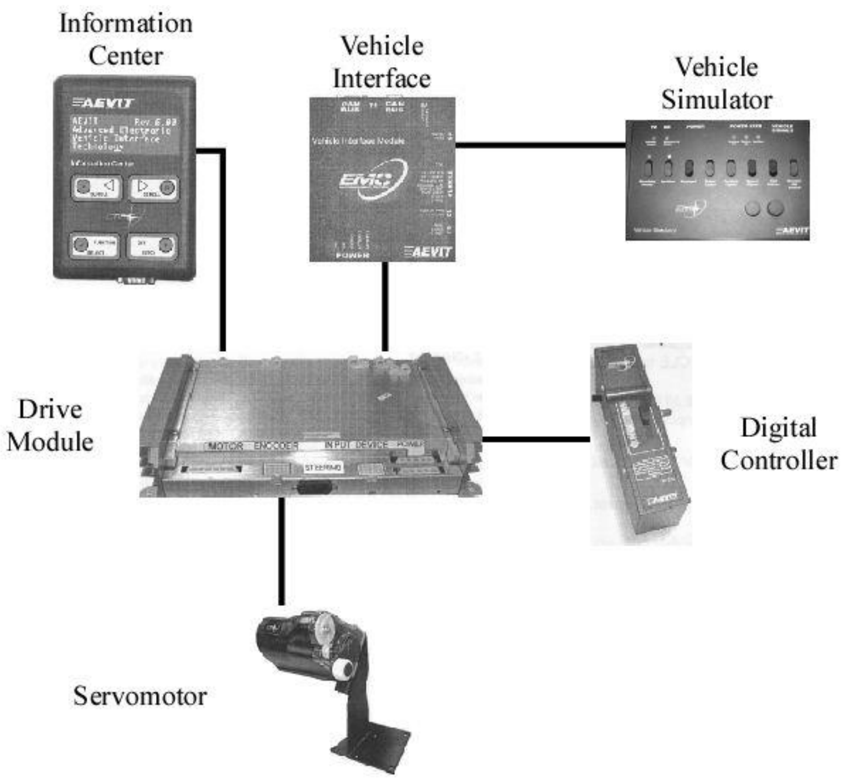


Figure 5.3 - AEVIT System Layout [38]

The *Information Center* is the interface that gives important data to the driver. This unit also shows what may be malfunctioning so that the necessary repairs can be made. It is equipped with four buttons labeled *Scroll* (left or right), *Select*, and *Esc*. These are used to navigate through the menus so that changes can be made to the program and diagnostic reports can be viewed. Furthermore, the *Esc* button can be used to power off the system once the vehicle has been parked and the ignition has been turned off.

The *Vehicle Interface* module gathers information about the vehicle and adjusts output accordingly. The unit is equipped so that a coil pulse and speed signal can be detected. The coil pulse uses information from the engine (typically from a fuel injector wire) to determine if the vehicle is running. Secondly, the speed signal relayed to the AEVIT vehicle interface module comes from the power control module on cruisecontrolled vehicles [38]. The output signal is important to the AEVIT system because the steering servomotor's rotational rate is scaled dependent upon speed. Full left steering input was given from the right steering endstop and the time it took for full rotation was recorded. The total degrees of rotation where divided by the travel time. Figure 5.4 shows this relationship. As vehicle speed increases between 0 and 25 mph or from 55 to 90 mph, the rate at which the steering wheel rotates is virtually constant. However, between 25 and 55mph, the rate decreases linearly as speed increases. This variable steering rate helps prevent oversteer at high speeds and understeer at lower speeds by altering the rate of rotation of the steering servo. During testing the AEVIT simulator speed was set to 15 mph, 55 mph, and 40 mph in the city routes, highway routes, and all other routes respectively so that the average vehicle speed matched the appropriate steering response. In the future, a system should be designed so that the setting can be dynamic and in accordance with the actual vehicle speed.

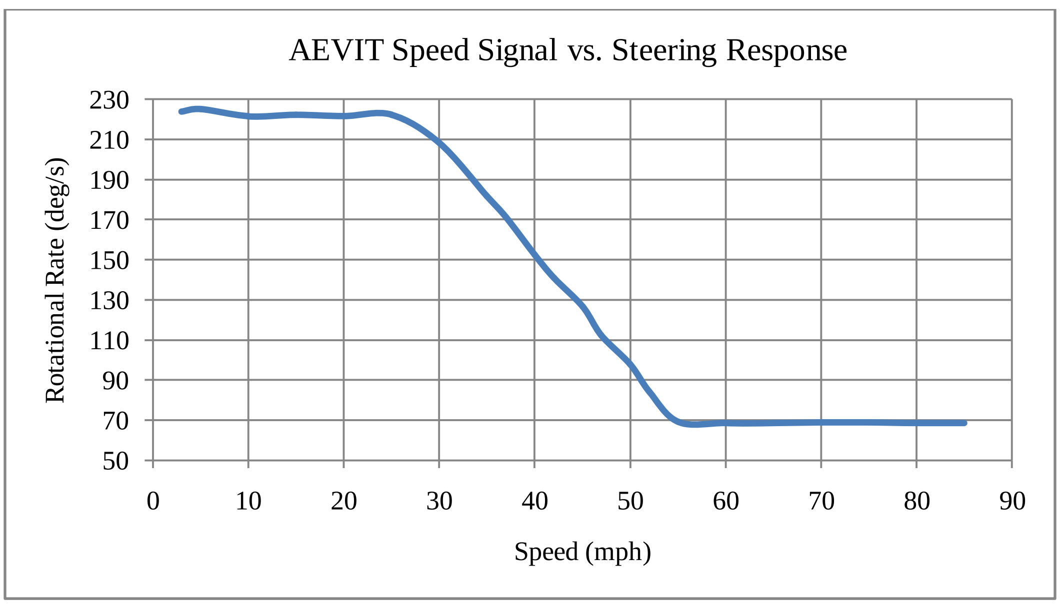


Figure 5.4 - AEVIT Speed Signal vs. Steering Response

Typically, the AEVIT system is connected to an actual running vehicle. However, for this study, hooking up the system to a running vehicle is neither feasible nor possible. For this reason, an AEVIT vehicle simulator module (Fig. 5.5) is used. This device is able to simulate signals that a vehicle ordinarily would deliver: ignition, coil pulse, speed signal, parking lights, brake lights. It also has a remote off switch.

Figure 5.5 - AEVIT Vehicle Simulator

The *Drive Module* is the main processing unit to the AEVIT system. Information from the input controller is processed and delivered to the servomotor encoder. Power is also distributed to the rest of the system from the *Drive Module*. Steering and gas-brake functions require separate servomotors. Therefore, a vehicle equipped with both steering and gas-brake controls, requires two of these modules as each can drive only one servomotor. The *Drive Module* contains four processors; EMC divides the unit into two sides with each side having an active and back-up processor. “The reason that four processors are used is to safely allow a single processor to reset itself while the system remains in operation. Each time the system is shut down and booted up again, the system will switch to the other side for main control [38].”

5.3 Input Devices

The AEVIT system can accept a wide variety of input devices making it versatile for a number of users. For persons with very little strength and limited range of motion, the 4-way joystick can be used. Whereas the person with a greater range of motion and strength might be prescribed a combination of two controllers (2-way joysticks, small steering wheel, gas-brake levers). All AEVIT controllers have redundant safety devices. When the system is activated, each controller uses three potentiometers to determine controller position. When these values do not match an error is recorded. In the event that one potentiometer fails, an audible alarm sounds but the system continues to operate uninterrupted. This project utilizes both a gas-brake lever/small steering wheel combination and a 4-way joystick during human-subject testing.

5.3.1 Gas-Brake Lever

A gas-brake lever (Fig. 5.6) is an input device that controls the gas and brake functions. It operates about a single axis, having a throw of about five inches. Using the information center, the lever can be setup so that the acceleration direction can be either forwards or rearwards. As a person pushes the lever forward, the resistance increases linearly, returning to center whenever no force is applied. Internally, on each side of the lever is an oil-filled shock that can be adjusted using tension clips. Since each side can be adjusted separately, the force required for forward and rearward action can be different [38]. Typical orthotic devices attached to the lever include a T-handle, splint, and tri-pin.

Figure 5.6 - AEVIT Gas - Brake Lever

5.3.2 Digital Steering Wheel

The digital steering wheel (Fig.5.7) is a small zero-effort steering controller. The reduced diameter, 6 inches, is ideal for individuals with limited range of motion in the hand. Full range of rotation is 6.875 turns. According to EMC, this is one of the most popular steering devices installed in modified vehicles due to its ease of use [38]. Intuitively, as a driver rotates the AEVIT wheel in the counterclockwise direction, the steering wheel rotates in the same direction, causing the vehicle to steer left. Moreover, a rotation in the clockwise direction causes the vehicle to steer right. Spinning orthotic devices such as a swiveling tri-pin, rotating pin, or spinner knob (Fig. 5.8) are commonly implemented.

Figure 5.7 - AEVIT Digital Steering Wheel

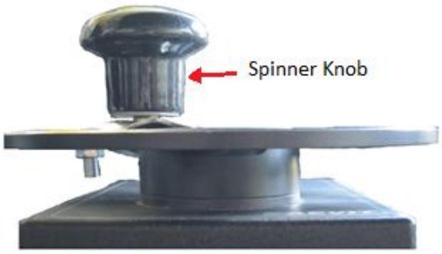


Figure 5.8 - Attached Orthotic Device

5.3.3 4-Way Joystick

For individuals with disabilities who have very little strength, range of motion, or use of only one hand, a joystick (Fig. 5.9) is typically prescribed. The 4-way joystick is considered a zero-effort device, combining gas, brake, and steering functions in one controller. Although it is not adjustable, the effort to move the joystick through its full range of travel is approximately 4 to 6 ounces of force [38].

Figure 5.9 - AEVIT 4-Way Joystick

This device, like the gas-brake lever, can be programmed so that the gas and brake directions (forward or rearward) can be reversed. Left or right steering motion of the vehicle is achieved by pushing the joystick left or right respectively. Adequate vehicle control is somewhat more difficult to maintain with the joystick. The driver must be able to independently control one function from the other. This requires well developed motor skills. For example, as a driver is making a turn, he or she is required to decelerate to a safe cornering speed and then accelerate the vehicle halfway through the turn. With the joystick, this action must be carried out while the appropriate angle to the left or right is held constant.

Furthermore, the joystick has a three control bands: centering, holding, and motion (Fig 5.10). The total range of motion of the controller is 60 degrees, 30 from each side of the center position. The centering band is activated whenever the joystick position is between $\pm$ 10 degrees of center. After the steering wheel has rotated, a driver can return it to center by holding the joystick within this range. The rate at which it returns to center is linearly proportionate to the proximity of the center position on the joystick. The closer to center, the faster it returns. The motion band is between 15 and 30 degrees from the center position on each side. When the joystick is held in this band, the wheel will rotate and continue to rotate until the endstop on the steering column is reached. As the position of the joystick approaches 30 degrees, the rate of rotation of the wheel increases linearly. In between the centering and motion bands is a 5 degree holding band, from 10-15 degrees on each side of the center. It is commonly used during extended turns where the wheel remains at a constant position. As the name suggest, the servomotor, and consequently, the steering wheel does not move in this band.

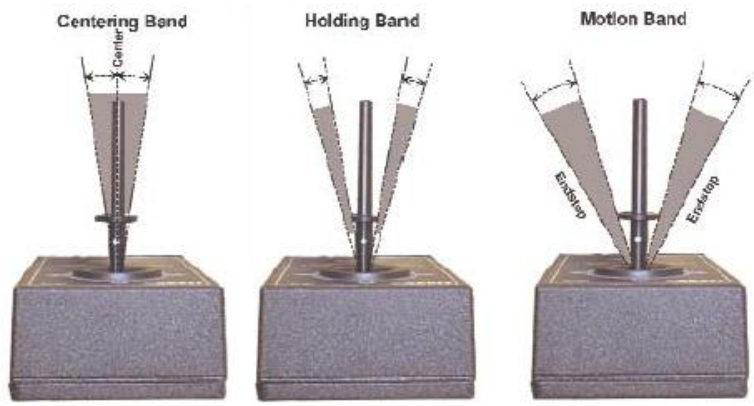


Figure 5.10 - Joystick Control Bands [38]

When the driver gives an input command from the joystick so that the actual steering wheel does not rotate more than $\pm$ 5 degrees from center it remains in what is called the drift band (Fig. 5.11). When the wheel is in this range, returning the joystick to center does not center the steering wheel. “The purpose is to allow the driver to make small alignment corrections without the wheel returning to center. This helps to compensate for wind, a crown in the road, or other factors that might cause a temporary change in the straight ahead center position of the vehicle. The Drift Band is not retained in memory so as soon as the steering wheel rotates past the 5 degree mark in either direction, the steering wheel will return to its original center position when the joystick returns to center [39].”

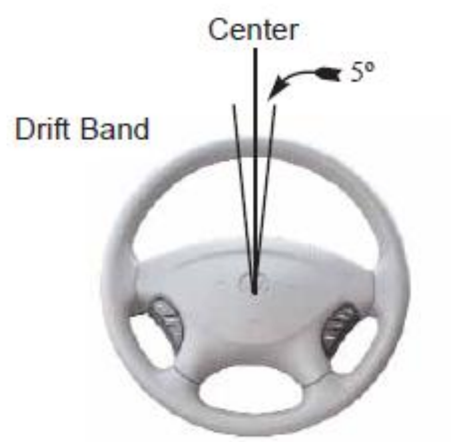


Figure 5.11 - Steering Wheel Drift Band [38]

5.4 AEVIT Controller Switch

During the course of this research study, it was necessary to change between different control systems. In order to do this, each controller had to be unplugged from the drive module and replaced with the next system of input devices. Each system has two controller plugs: one for the gas-brake controller and another for the steering controller. The AEVIT system, however, is designed so that these are very difficult to unplug. This prevents the interface from becoming disjointed when in use in a vehicle. Additionally, these wires in the connectors are very delicate and could be damaged from repetitive installation and removal.

For these reasons, a simple, easy-to-use switch was proposed and developed by Matt Wills. It was important that it be able to switch between the two systems in one step. Ordinary switches typically can only switch between 2 or 4 contacts at a time. The AEVIT controller however has two sets of 12 pin connectors. Therefore, in order to switch between the two control systems a larger switch had to be used.

Figure 5.12 - AEVIT Controller Switch

The AEVIT controller switch utilizes a manual, two-position rotary switch to change between the gas-brake/steering controller combination and the 4-way joystick. The separate inputs can be switched to a common output to the AEVIT system that is read by the drive modules. The male connectors at the terminal end of each controller plug into the appropriate 12-pin female connector on a printed circuit board. Each of the two systems, have one plug for gas-brake and steering. As seen in Figure 5.12, the top view of the printed circuit board shows the layout of the terminals. The top row is for the gas-brake connectors while the lower row holds the steering connectors. The first, second, and third columns hold the joystick inputs, outputs, and gas-brake/steering combination inputs respectively. The front face of the switch shows that the up position selects the gas-brake/steering wheel controls and the lower position selects the joystick controller. All of the components of the switch are housed in an aluminum enclosure. A parts list and printed circuit board trace diagram can be found in Appendix D.

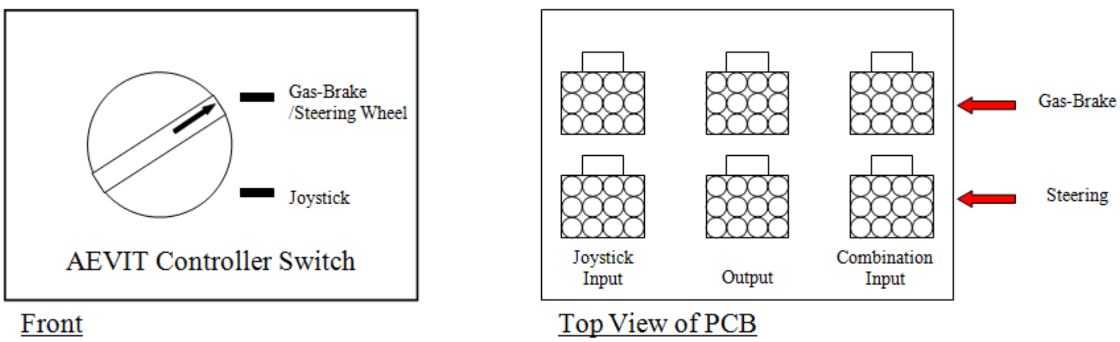


Figure 5.13 - AEVIT Switch Diagrams

5.5 Simulator – AEVIT Control System Integration

One of the goals of this research project is to determine the effectiveness of using DBW controls for training individuals with disabilities. For this reason the SSI simulator and the EMC AEVIT controls system had to be integrated. The SSI simulator, unlike a real vehicle, has a nearly horizontal steering column and the pedals are simply connected to potentiometers to give the computer acceleration and braking inputs. The steering wheel gives the simulator software data that indicates where the steering wheel is at. In order for the simulator to work properly, these values must be present and within expected ranges.

Furthermore, when an authorized mobility equipment dealer installs an AEVIT steering servomotor, it is linked directly to the steering column. This drives the steering wheel but also, more importantly, allows a third party to disengage the servo drive without its complete removal. The study involves the use of both an AEVIT controlled vehicle and a pedal/steering wheel controlled vehicle. Thus, the two systems had to be linked in a similar way; the AEVIT system had to be able to be disengaged without removal.

In order for the simulator to provide a more immersive environment for the user, the driver needed to feel as if he or she was driving from the left side of the vehicle. The SSI simulator is large and requires an equally large flat surface on which to sit. The shell of the van did not have an adequate space. Furthermore, it was not feasible to remove the SSI steering column and remotely locate the assembly, along with its measuring devices (potentiometers). Therefore, the van required modification so that the SSI unit could sit on the driver's side of the vehicle. A large enough section of the driver's side firewall was cut away (Fig. 5.14) to provide free space where a platform could be installed. The platform is supported by the remaining portion of the firewall and a supplemental support bracket (Fig.5.15).

Figure 5.14 - Firewall Cutout (courtesy of Matt Wills)

Figure 5.15 - Support Bracket (courtesy of Matt Wills)

Figure 5.16 shows the platform mounted with the support bracket installed. The gas-brake servo is mounted below the platform on a cross member. The two vertical tabs are present so that the SSI unit can be safely bolted to the vehicle.

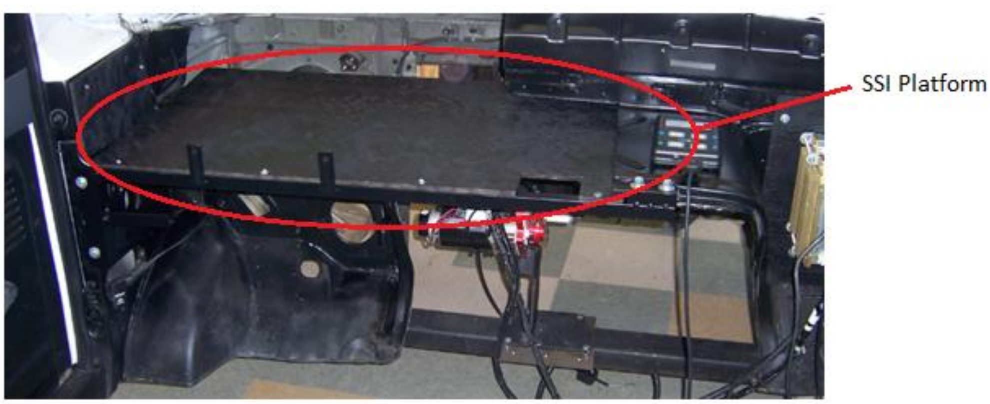


Figure 5.16 - SSI Platform (courtesy of Matt Wills)

After the SSI simulator is placed on the platform, a mechanical connection is still required for the DBW system to function in conjunction with it. A bearing assembly bracket was designed to support the linkage.

Figure 5.17 - Bearing Assembly Bracket (courtesy of Matt Wills)

The bearing assembly "wings" attach to the support bracket. It holds the servo motor shaft and the servomotor mounting bracket. The gear on the left is part of the servomotor system.

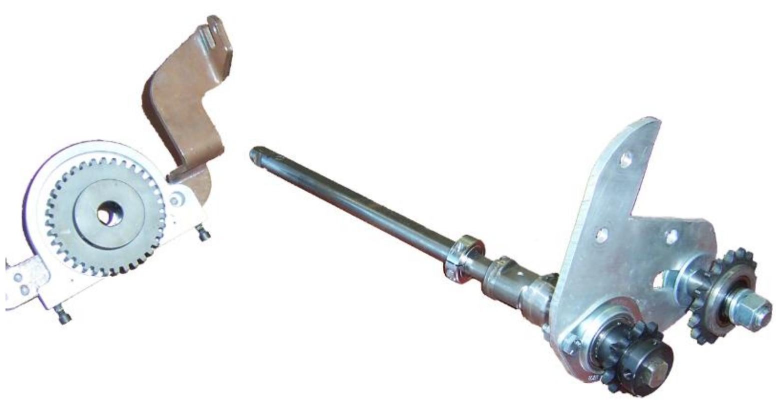


Figure 5.18 - Servomotor Mounting Bracket and Shaft (courtesy of Matt Wills)

The steering gear assembly is pictured below in Figure 5.19. The servomotor shaft attaches to the assembly via a universal joint. This is required due to the fact that the servomotor shaft and the steering wheel do not rotate about parrallel axes. This does increase the resitance to rotation somehwat; however, it is not enough to affect performance.

Figure 5.19 - Universal Joint (courtesy of Matt Wills)

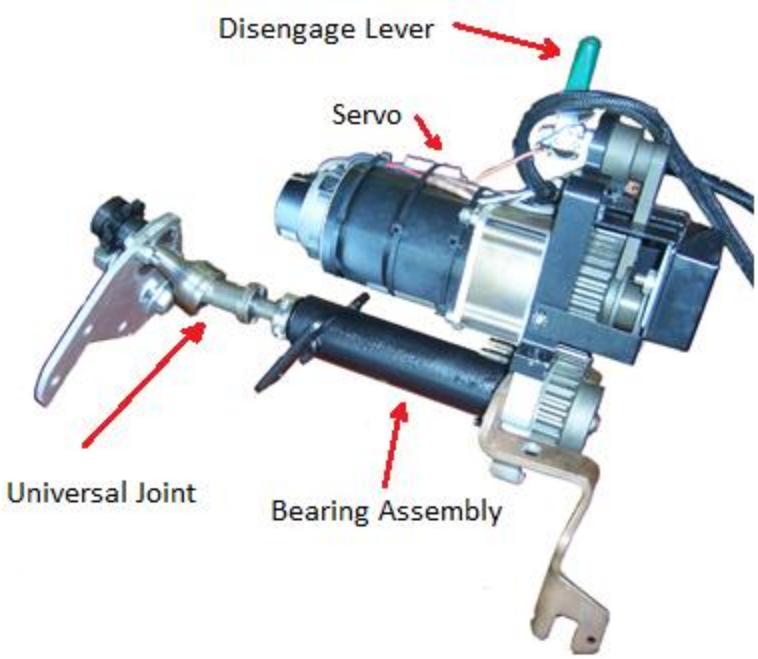


Figure 5.20 - Assembled Steering Unit (courtesy of Matt Wills)

The assembly of the steering unit can be seen in Figure 5.20. The servo motor can easily be disengaged in the event that a user needs to use the standard vehicle steering wheel. The AEVIT servomotor is equipped with a lever (green in the picture above) that, when in the position shown, engages the servomotor to the steering wheel . When the lever is rotated 90 degrees, the unit becomes disengaged. Figure 5.21 shows the entire assembly installed in the vehicle shell. Two spur gears and a tensioner mounted to a ¼" aluminum plate make up the gear train. The servomotor shaft is connected to the SSI wheel by this chain drive. A fiberglass cover was fabricated and installed over the spur gears to eliminate the risk of bodily injury.

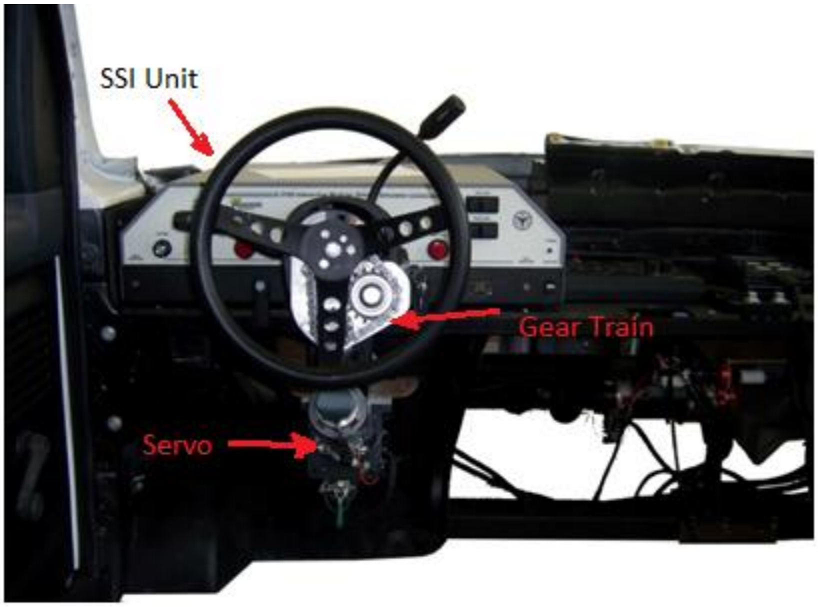


Figure 5.21 - Complete Assembly

The gas and brake pedals are actuated by a different servo motor. As the servo rotates, it wraps a steel cable around its shaft. The cable, being connected at the other end to the gas or brake pedal, pulls the pedal down as if it were being pressed by a foot. Since this is not a rigid link, it is not necessary to disengage the cable before using the system without the AEVIT interface.

It is important to note that the van is actually never physically moving. The GB lever is placed to the left of the SSI whereas the small steering wheel is placed to the right of the driver. When the joystick is used, it is placed to the right of the user. The setup was done so that it similarly resembles actual vehicle modifications.

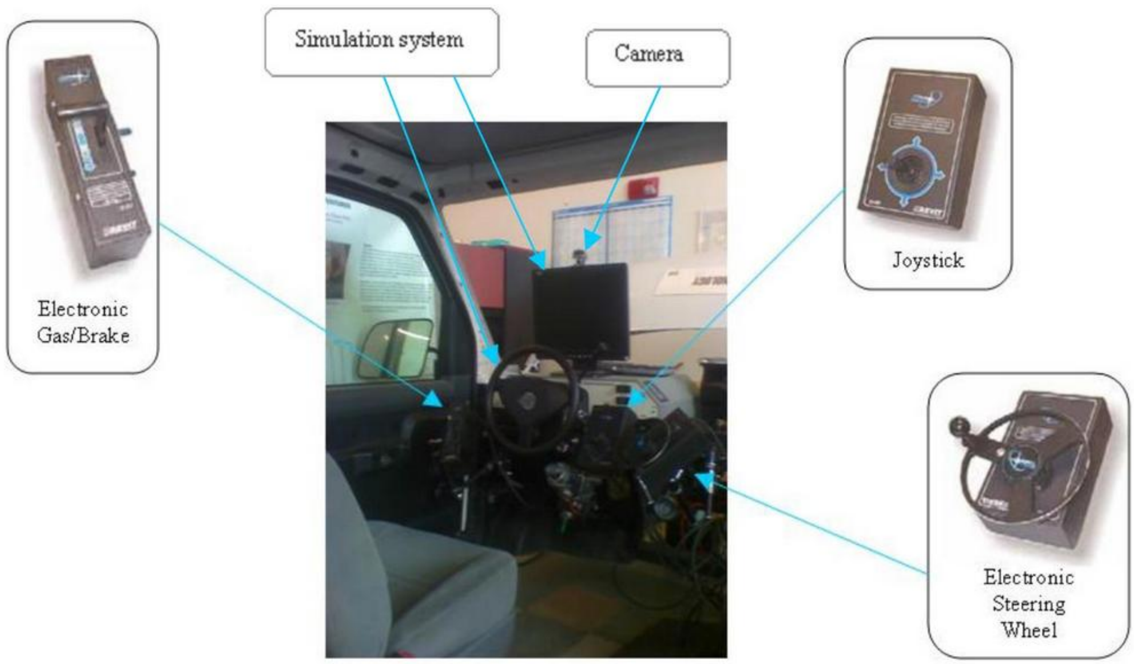


Figure 5.22 - Final Setup

The reaction time in the acceleration and braking test data using DBW control was skewed in that the actual reaction time was affected by a delay in the servo system setup. The SSI system measures the reaction time as the time it takes a driver to remove their foot from the accelerator and begin applying the brake. When using the DBW systems for acceleration and braking, the servo system must receive the input and deliver the relative output command to the servomotor. The brake pedal is then applied only after the servomotor takes up the slack in the accelerator cable and then begins to engage the brake cable, consequently registering a reaction time the SSI simulator. Some tests were conducted to determine what those values were. A Tektronix TDS-1002 2-channel oscilloscope was used with two PCB Electronics accelerometers to determine the delay. Input signals were filtered. Furthermore, results in Chapter 7 for DBW reaction times were reduced and determined by the following equation:

Actual Reaction Time = SSI Reaction Time – Pedal Lag – Servo Output Lag

Table 5.1 - Joystick Acceleration/Braking Delay

	Pedal Lag			Servo Output Lag		
Trial	Cursor 1	Cursor 2	Delay (s)	Cursor 1	Cursor 2	Delay (s)
1	1.82	2.36	0.54	0.108	0.148	0.04
2	1.18	1.64	0.46	0.1	0.14	0.04
3	2.86	3.32	0.46	0.032	0.076	0.044
4	2.82	3.28	0.46	0.016	0.056	0.04
5	0.9	1.34	0.44	0.516	0.556	0.04
		Average =	0.472		Average =	0.0408
		Std Dev =	0.038987		Std Dev =	0.001789

Table 5.2 - GB Acceleration/Braking Delay

	Pedal Lag			Servo Output Lag		
Trial	Cursor 1	Cursor 2	Delay (s)	Cursor 1	Cursor 2	Delay (s)
1	0.33	0.79	0.46	0.224	0.292	0.068
2	-0.15	0.31	0.46	0.104	0.176	0.072
3	0.28	0.75	0.47	0	0.072	0.072
4	0.16	0.62	0.46	0.336	0.404	0.068
5	0.08	0.53	0.45	0.016	0.084	0.068
		Average =	0.46		Average =	0.0696
		Std Dev =	0.007071		Std Dev =	0.002191

The servo output lag and pedal lag were unaffected by the selected AEVIT simulator module speed setting. Average response time for the joystick (when the AEVIT simulator module was set to 40 mph) equaled the response times when unit was set to 80 mph and 15 mph.

When the steering response time was tested, it was found that the average delay for the joystick was about 0.017s. The GB/S system had an average response time of 0.031s. This was approximately twice the joysticks lag. It must also be noted that the lag times were unaffected by the vehicle speed setting on the AEVIT simulator module.

Table 5.3 – Steering Lag Times

	Joystick Delay			GB/S Delay		
Trial	Cursor 1	Cursor 2	Delay (s)	Cursor 1	Cursor 2	Delay (s)
1	0.324	0.344	0.02	0.012	0.052	0.04
2	0.068	0.084	0.016	0.076	0.104	0.028
3	0.084	0.096	0.012	0.052	0.076	0.024
4	0.116	0.132	0.016	0.128	0.16	0.032
5	0.092	0.112	0.02	0.1	0.132	0.032
		Average =	0.0168		Average =	0.0312
		Std Dev =	0.003347		Std Dev =	0.005933

Chapter 6: Human Subject Testing

6.1 Methods

In an effort to determine the effectiveness of using the AEVIT controllers in a virtual environment, a human subject study was completed (IRB approval #107994). The sample consisted of 30 individuals from three groups: able-bodied individuals (Group 1, n=10), elderly individuals (Group 2, n=10), and individuals with disability (Group 3, n=10). An effort was made to obtain a sample that consisted of ratio of male to female of 1 to 1.

Table 6.1 – Sample Characteristics

		Able-bodied n=10	Elderly n=10	Disability n=10
Gender	*Male*	5	5	7
	Female	5	5	3
Age (avg.)		36	72	39.8

Each of the subjects involved in the study gave their informed consent prior to the start of any type of testing. All participants at the time of testing held a valid driver's license, were capable of using both hands, and were able to receive verbal instructions. Participants who require a form of hearing aide were permitted. Drivers who used manual or DBW controls for driving fell into the category of individuals with disability, regardless of age. The study did not include individuals with a disability who use adaptive foot controls.

After giving consent, drivers were asked to sit inside of the shell of a van (front portion only). A common vehicle seat was used for individuals who do not use a wheelchair while driving. If the height of the seat was inappropriate, a seat pad was allowed so that the driver could see the viewing screen and access all of the controls. For those who use and chose to stay in their wheelchairs, the vehicle seat was removed. A seatbelt attached to the vertical column was available; however, most persons chose to not use it. Furthermore, the van shell rests on four castors and can be raised or lowered as required. The van is stationary and does not move in any way.

During testing, the subjects were videotaped from two angles: a face view and side view so that hand motions (and foot motions in some cases) could be observed and viewed at a later time. Three types of tests were given with three types of control systems defined as:

1. Standard steering wheel and gas/brake pedals
2. DBW joystick controller
3. DBW steering wheel and gas/brake controllers

System 1 involved the use of only the SSI simulator while systems 2 and 3 utilized the AEVIT DBW adaptive control system in conjunction with the SSI virtual environment. Individuals who have a disability were unable to utilize the gas/brake pedals in the SSI system and where, consequently, excluded from testing for that type of system.

Table 6.2 shows a visual representation of the tests administered to each group.

Table 6.2 – Testing Matrix

	Group 1	Group 2	Group 3
Acceleration/Braking	● ● ●	● ● ●	● ●
Steering	● ● ●	● ● ●	● ●
Driving in Traffic	● ● ●	● ● ●	● ●

System
- ● Standard steering wheel and gas/brake pedals
- ● DBW joystick controller
- ● DBW steering wheel and gas/brake controllers

The order in which each system was used was randomized for each person prior to testing. This order was maintained throughout each test. If, for instance, a driver was randomly selected to use system 1, 3, then 2, all tests would be administered on the systems in that order.

Furthermore, each person was given following basic instruction on how to use each DBW control before beginning the acceleration and braking test with that controller.

For the digital steering wheel:

1. Counter-clockwise rotation causes the vehicle to turn left.

2. Clock-wise rotation of the wheel causes the vehicle to turn right.

For the gas/brake lever:

1. Pushing the lever forward will cause the vehicle to accelerate.
2. Pulling the lever rearward will cause the vehicle to decelerate and eventually stop.

For the 4-way joystick:

1. Pushing the joystick forward causes the vehicle to accelerate.
2. Pulling back on the joystick will cause the vehicle to decelerate and eventually stop.
3. To turn left, push the joystick to the left.
4. To turn right, push the joystick to the right.
5. Tap the joystick in either to make small lane adjustments.
6. Holding the joystick to the left or right for small adjustments will likely cause the vehicle to oversteer, resulting in a loss of control.

Information related to the different joystick control bands was withheld from the driver.

An attempt was made so that the DBW controls were placed in a manner so the participant's wrist and arm were in a comfortable position from the armrest. The three types of tests using the aforementioned driving systems are detailed in the following subsections.

6.1.1 Acceleration and Braking Test

The acceleration and braking test was administered to each individual on each applicable system over three trials. Before starting, it was explained that the driver was to start the vehicle and accelerate to 50 mph per hour (Fig. 6.1). At that point a stop sign would appear on the screen and they were to quickly come to a complete stop. A practice trial was allowed at the beginning of testing for each system so that the user could become familiar with the task being given and the basic function of the controls. The individual was then asked if they understood the task and questions were answered.

Figure 6.1 - Acceleration and Braking Test Instructions

Figure 6.2 – Acceleration and Braking Test Start Position

At the start of the test, the vehicle sits at rest near the side of a straight track. The road is straight with short walls to either side (Fig. 6.2). The driver was asked to start the vehicle with the key and shift into drive using the lever on the column and reminded to accelerate to 50 mph. Once the vehicle was shifted into drive, it would roll forward if the brake was not applied. A large stop sign appeared in the center of the screen a short time after the vehicle reached the designated speed. After the vehicle was stopped, if the driver released the brake before coming to a complete stop, they were asked to hold the brake until the screen changed.

Figure 6.3 - Stop Command Issued

Results were displayed to the driver on the screen. Quantitative data was taken on the speed of the vehicle, reaction time, stopping distance, reaction distance and braking distance as seen in Figure 6.4. Notable observations and a video of the driver's performance were also recorded.

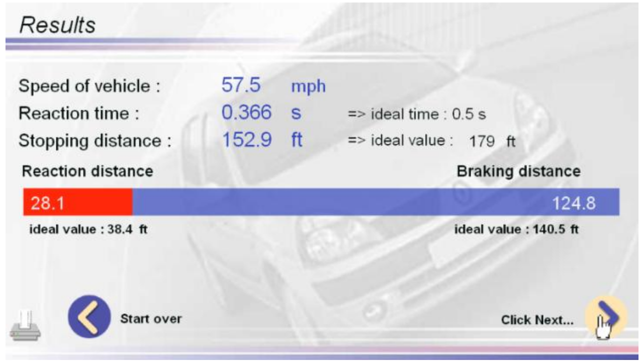


Figure 6.4 - Sample Braking Results

6.1.2 Steering Test

The steering test was composed of several straight and turning sections. At the beginning of the steering test, the study participant was given audible instructions and the screen displayed the exercise guidelines (Fig. 6.5) and the driver's vehicle sat in park in the middle of the right lane on a two-lane road (Fig. 6.6).

Figure 6.5 - Steering Instructions

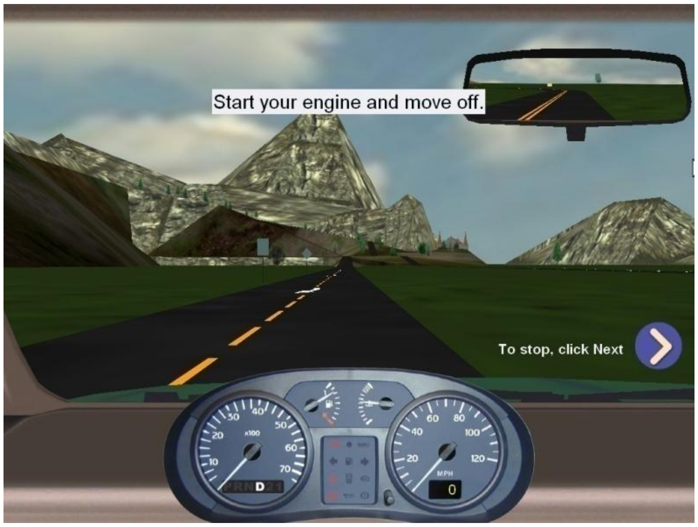


Figure 6.6 - Steering Test Start Position

As the driving course progressed, the posted speed limits changed between 20 and 55 mph. The driver was told that the route begins with a speed limit of 30 mph and to obey all traffic laws while driving. Furthermore, the driver was informed that they were being graded on their ability to maintain their lane position and their speed relative to the posted speed limit. The route began with a straight level path, eventually leading to a short climb. After the climb, the posted speed was reduced to 20 mph; a 180 degree smooth right-hand turn followed.

Figure 6.7 - Steering Test 180 Degree Turn

A downhill grade led to a long straightway where the speed limit increased to 55 mph. At the end of the straight path, the speed limit was reduced and the participant was instructed to follow the road into a roundabout, taking the first exit available. Out of the turn, the road widened, then narrowed, and the participant was eventually asked to stop next to a yellow sign near an interstate highway entrance (Fig. 6.8).

Figure 6.8 - Steering Test End Position

The test was administered only once with each of the systems. Notable observations and lane width, lane position, vehicle speed, and posted speed were recorded at 0.2 second intervals.

6.1.3 Driving in Traffic

A pair of test courses was designed to incorporate both city and highway driving in an effort to better understand the performance of each of the driving controls. The SSI simulator is equipped with a virtual city/highway environment that has eight different starting positions (4 city, 4 highway). The SSI menu labels these points “A” through “H.” The city route “A” and highway route “E” were used in testing. Traffic was set to “Low,” time of day was set to “Day,” visibility to “Clear,” precipitation to “None,” and error checking were turned "ON" (Fig 6.9, route "A" – left, route "E" - right). With error checking, the driver is notified of the driving infractions being committed as they are being made. A screenshot of each driving error can be found in Appendix G.

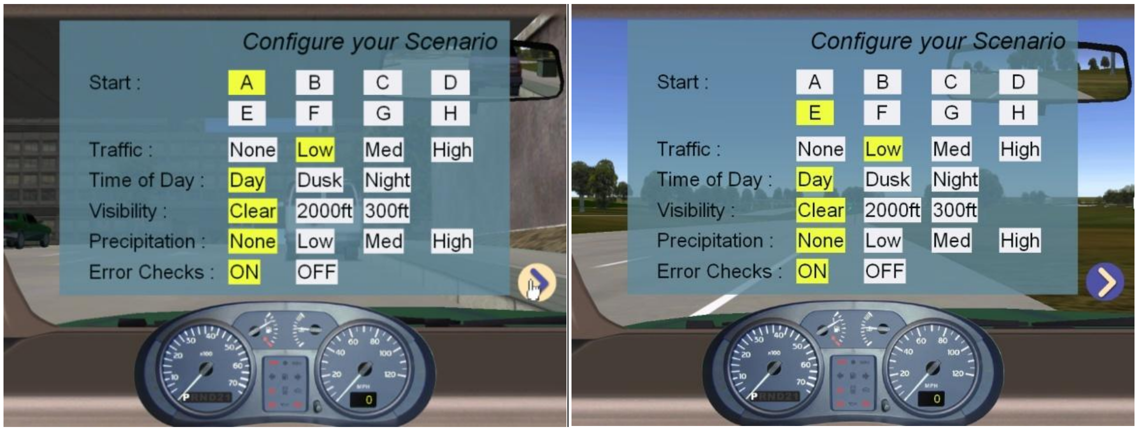


Figure 6.9 – Traffic Driving Scenario Configurations

The simulated vehicle began on the side of an uphill one-way street, parallel parked on the right in route "A" (Fig. 6.10). The driver was told to start the vehicle, pull out, and make the first available right turn when it was safe to do so. The route ended when the driver parked next a wall with graffiti on it (Fig. 6.11).

Figure 6.10 - Route "A" Start Position

Figure 6.11 – Route "A" End Position

The vehicle on Route "E" began on the right shoulder of a highway. The traffic in the traveling lanes to the left was going at highway speeds. The driver was asked to start the vehicle, obey all traffic laws, and pull out and join traffic when it was safe to do so. It is worthy of noting that, at the beginning of the route, the driver must quickly merge onto the road before colliding with the sign on the shoulder ahead. The route continued until the driver either crashed or reached the end of the route. The starting (left) and ending (right) positions are shown in Figure 6.12.

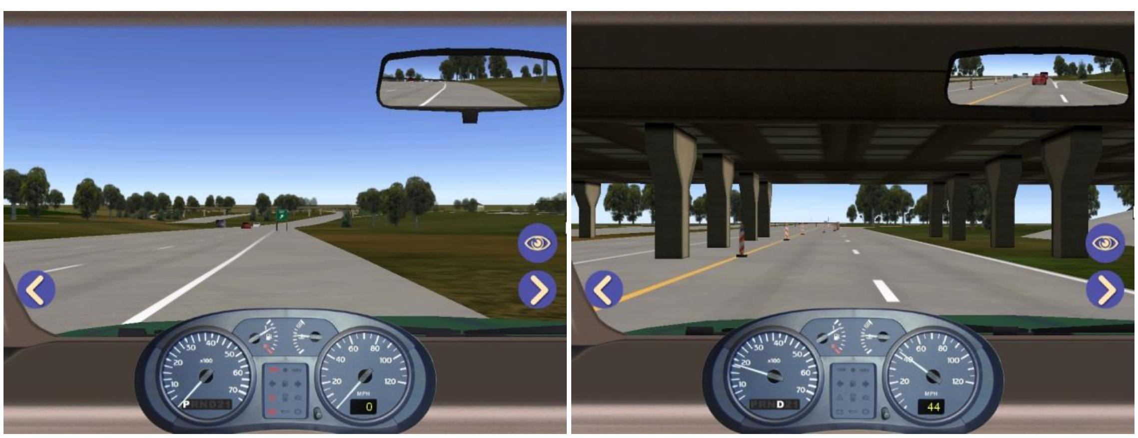


Figure 6.12 – Starting and Ending Positions of Route "E"

For all cases, each participant was asked to obey all traffic laws and to listen for directions for an audible route to follow. Individuals were also reminded that they were not to use the parking lane on the side of the road as a turning lane. Right turns on red were disallowed. The instructions were given so that the participant had enough time to react and safely maneuver the vehicle into the appropriate position. Route “A” was designed to last about 5 minutes while route “E” was intended to last about 3 minutes. The specific instructions that were given to each driver are as follows:

Route “A” - Approximate time - 5 minutes

1. Take first right.
2. Go through intersection.
3. Take a right.
4. Take a left at the dead end.
5. Take next left.
6. Take next left.
7. Take next right.
8. Park on left side of road next to wall with graffiti on it.

Route “E” – Approximate time – 3 minutes

1. Merge into traffic.
2. Go under the overpass.
3. Get into left lane.
4. Exit the interstate where cones force you to do so.

Total scenario time, speed infractions (quantity and duration), inadequate space cushion (quantity and duration), improper lane position (quantity and duration), turn signals missed (quantity) and dangerous intersection crossings (quantity), and notable observations were recorded. The results were displayed on the screen so that the driver could see them (Fig. 6.14).

If for any reason, a driver crashed at the very beginning of the test, the test was restarted and the driver was given another try. However, if the crash was not sever and the simulation did not end, the driver was allowed to put the vehicle into reverse, back up off of the obstacle and continue on the way when the path was clear. If the driver missed an instruction and did not follow the given route directions, he or she was asked to complete make the same type of turn at the next possible opportunity. The driver then completed the test on a similar parallel route.

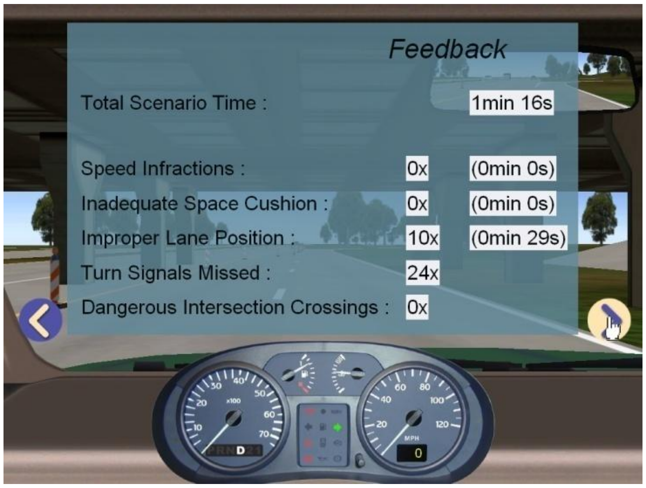


Figure 6.13 - Sample Feedback Screen

6.2 Driving Performance Survey

Before, between, and after each test, the participants were asked a series of questions about their opinions on the separate control systems. If the participant had used a DBW system before the beginning of testing, information was requested on their views of their adaptive equipment. The testing questions related to their views of the systems safety, ease of learning to use, system ease of use, system reliability, their ability to control gas, brake, or steering, level of confidence, ease of operation, proficiency, and realism of each scenario. Additionally, questions relating standard driving equipment to DBW controls were asked to the able-bodied and elderly groups. A sample copy of the participant survey can be found in Appendix F.

Chapter 7: Results and Discussion

7.1 Evaluation of Acceleration and Braking Performance

The results of the acceleration and braking test can be found in Table 7.1. As previously noted, GB/S stands for gad-brake system with small steering wheel and NDBW stands for standard vehicle controls (No DBW). For this test, the stop sign appeared a short time after the vehicle reached 50 mph.

Table 7.1 - Average Acceleration and Braking Test Results

Maximum Speed (mi/hr)	NDBW	GB/S	Joystick
18-64	56.6	56.6	56.4
65+	49.9	50.2	55.6
Disability		56.5	55.7

Reaction Time (s)	NDBW	GB/S	Joystick
18-64	0.788	0.537	0.7
65+	0.694	0.565	0.7
Disability		0.560	0.632

Braking Distance (ft)	NDBW	GB/S	Joystick
18-64	122.72	127.06	127.9
65+	106.21	111.33	126.4
Disability		126.34	124.73

Stopping Distance (ft)	NDBW	GB/S	Joystick
18-64	182.18	207.64	215.0
65+	157.51	192.78	213.7
Disability		208.54	210.81

For group 1, the average maximum vehicle speed was about the same for the standard vehicle controls, in addition to both of the DBW control systems. For group 2, it was found that the largest average maximum vehicle speed was acquired when participants were using the joystick. For Group 3, individuals with disability, average maximum vehicle speed was 0.8 m/hr faster when using the GB/S system versus the joystick system.

Table 7.2 - Average Reaction Time Standard Deviations

NDBW	Max Speed (mi/hr)	Reaction Time (s)	Stopping Distance (ft)
18-64	1.173030264	0.219503832	19.85810933
65+	2.166527061	0.238125561	17.75048311
Disability	-	-	-

GB/S	Max Speed (mi/hr)	Reaction Time (s)	Stopping Distance (ft)
18-64	1.134226228	0.162649225	15.89806107
65+	1.520968665	0.167780265	19.60839178
Disability	1.03413947	0.165268745	15.32008647

Joystick	Max Speed (mi/hr)	Reaction Time (s)	Stopping Distance (ft)
18-64	1.124255584	0.170940622	18.98543431
65+	2.177335556	0.244635975	28.14128486
Disability	2.072628795	0.387068654	26.78736579

The reaction time was fastest (0.537s, 0.565s, 0.560s for Groups 1, 2, 3 respectively) for all three groups when the GB/S system was used. For group 1, the reaction time was 0.088 seconds slower when the NDBW wire system was used versus the joystick. On the other hand, in elderly drivers, the opposite was true. The NBDW system reaction time was faster than the joystick by 0.006 seconds. Group 3 drivers were able to exhibit a reaction time of 0.560 seconds, on average, using the GB/S. Their time was 0.072 seconds slower using the joystick. It must be noted that the reaction times listed in Table 7.1 are adjusted from what the SSI system measured. The measured reaction time was reduced by 0.53 seconds for the GB/S system and 0.51 seconds for the joystick system (Fig. 7.1). A detailed explanation of the adjustment can be found Chapter 5.5. It's important to note that there is an adjustment to the reaction times in these results are reduced from the actual measured values by approximately 0.5 s for each of the systems.

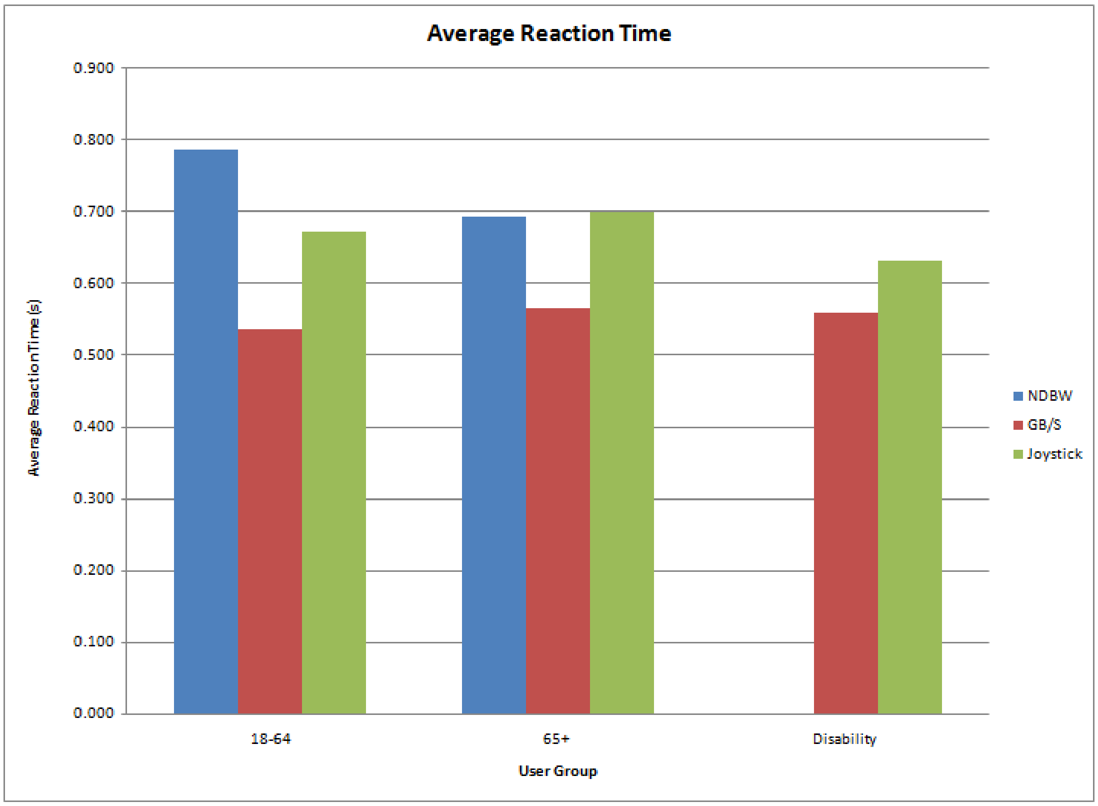


Figure 7.1 - Average Reaction Time

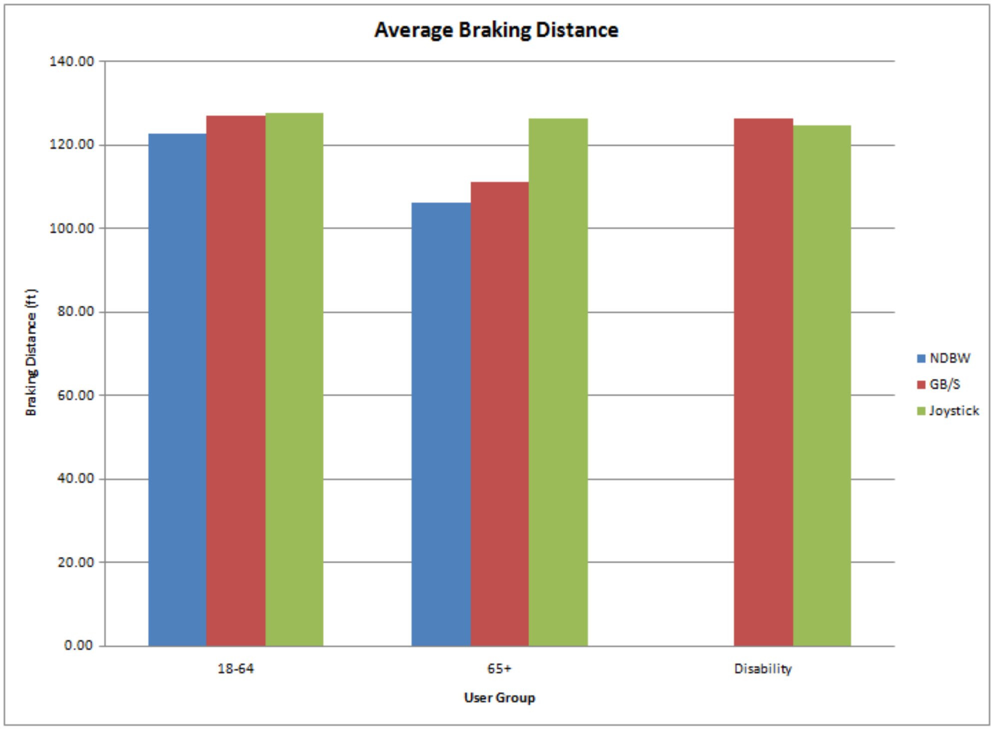


Figure 7.2 - Average Braking Distance

Despite the lag incurred by the servo system, it realistically shows how far the vehicle would travel before coming to a complete stop. In all cases, drivers were able to stop faster when using the GB/S system than when using the joystick system. Furthermore, participants in Groups 1 and 2 were able to brake the fastest when using the standard controls. Braking distance is a variable based on maximum vehicle speed and cannot readily be used to determine driver performance for the vehicle control systems.

7.2 Evaluation of Steering Data

The steering test was a very good indicator of how the participant could maneuver the vehicle along straight path and around a simple curve. Since drivers in Groups 1 and 2 have driven with standard vehicle controls for some time and can safely do so in the real world, their performance using this system in the virtual environment should follow suit. Indeed, results did show that drivers using the NDBW system made fewer errors while maintaining a speed closer the posted speed limit.

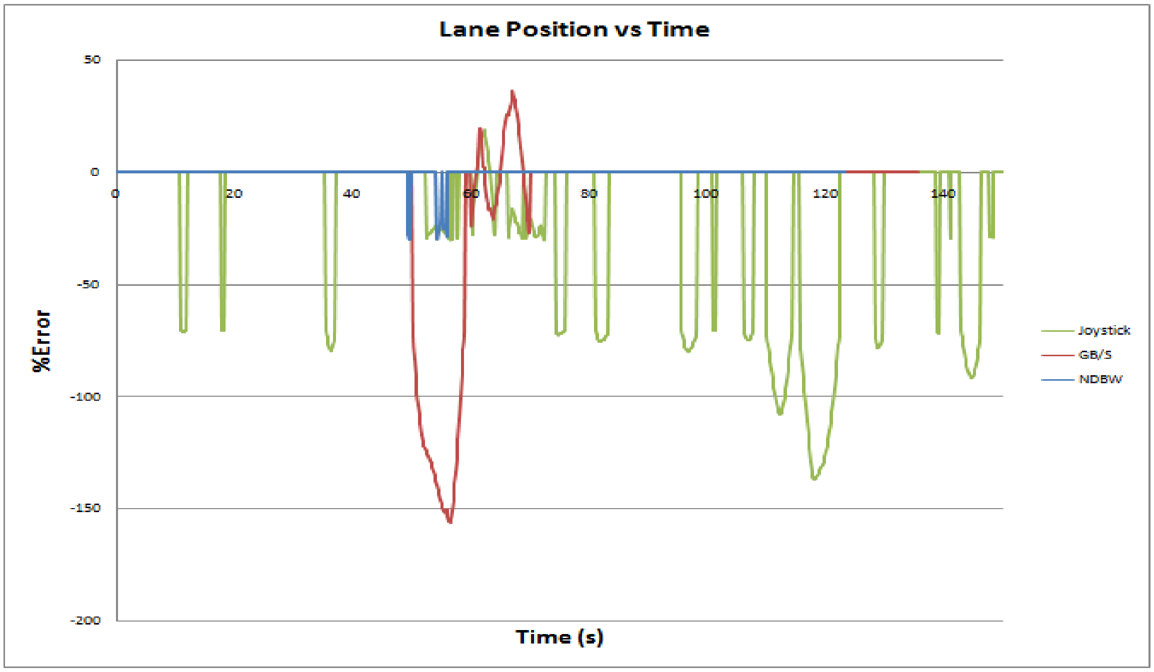


Figure 7.3 - Sample Steering Data (Group 1, participant 1, lane position)

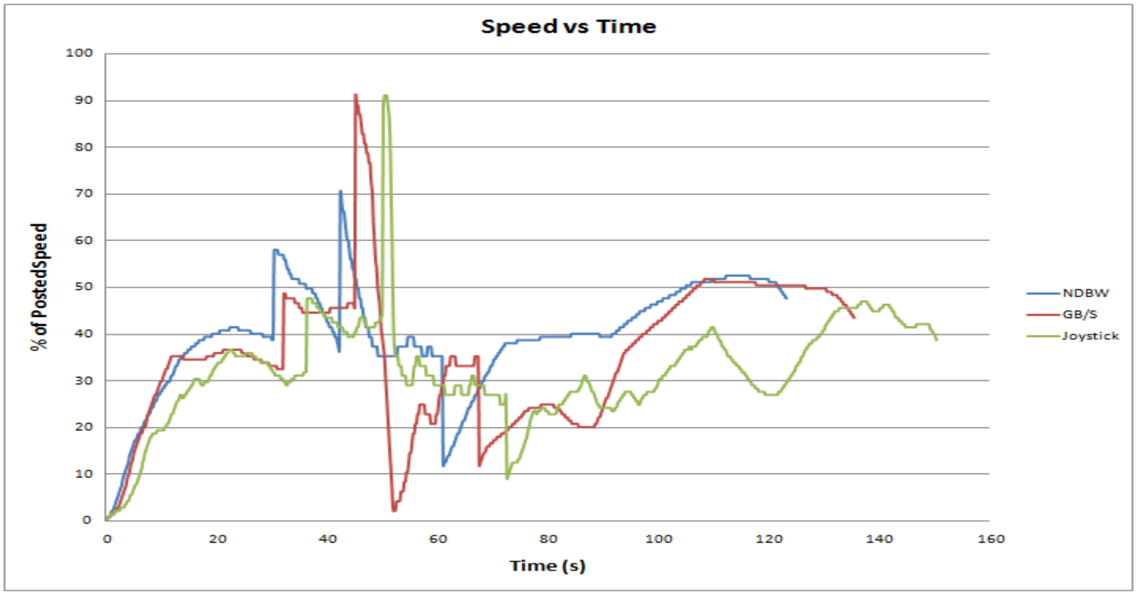


Figure 7.4 - Sample Steering Data (Group 1, Participant 1, speed)

Figures 7.3 and 7.4 show a general trend of most of the drivers. Lane error was calculated by:

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*

The NDBW system was marked by the least lane position errors, higher average posted speed, and typically completion of the designated route in a shorter time frame. In figure 7.3, the % error is the relative distance that the vehicle is outside of the lane. 100% on the y-axis means that the vehicle is one full lane width outside of the lane. In this case, it is evident that the driver had the most difficulty maintain lane position when using the joystick. Moreover, when using the NDBW system, there were only three instances over the entire route when the vehicle was outside of the lane. Table 7.3 shows the relative velocity in terms of posted speed. Sharp vertical lines in the graph represent a change in the posted speed. In general, drivers were able to maintain the highest percentage of the posted speed when using the NDBW system. Secondly, the GB/S system had the next highest speeds. Finally, the average joystick speeds were the lowest of the three systems.

Table 7.3 - Summary of Steering Results

	NDBW		GB/S		Joystick	
	Speed	% Abs Error	Speed	% Abs Error	Speed	% Abs Error
Able Bodied	39.45	7.94	35.09	36.98	28.44	64.18
Elderly	39.57	15.68	28.85	61.34	21.50	81.07
Disabled	N/A	N/A	33.14	54.10	33.43	54.15
AVERAGE	39.51	11.81	32.36	50.81	27.79	66.47

Note: Speed is in miles per hour

Table 7.2 shows the average percentage of the posted speed and the percent absolute error for of all drivers on each of the three systems. The percent absolute error is dependent on the vehicle's distance and time outside the lane. Groups 1 and 2 maintained nearly the same percentage of the posted speed when using the NDBW system at about 39.5%. However, Group 1 had about half of the position errors as Group 2. When using the GB/S system, Group 1, 2, and 3 maintained 35.1, 28.9, and 33.1 percent of the posted speed and had 37.0, 61.3, and 54.1 percent lane position error respectively. Using the joystick system, Group 1, 2, and 3 maintained 28.4, 21.5, and 33.4 percent of the posted speed and had 64.2, 81.1, and 54.2 percent lane position error respectively.

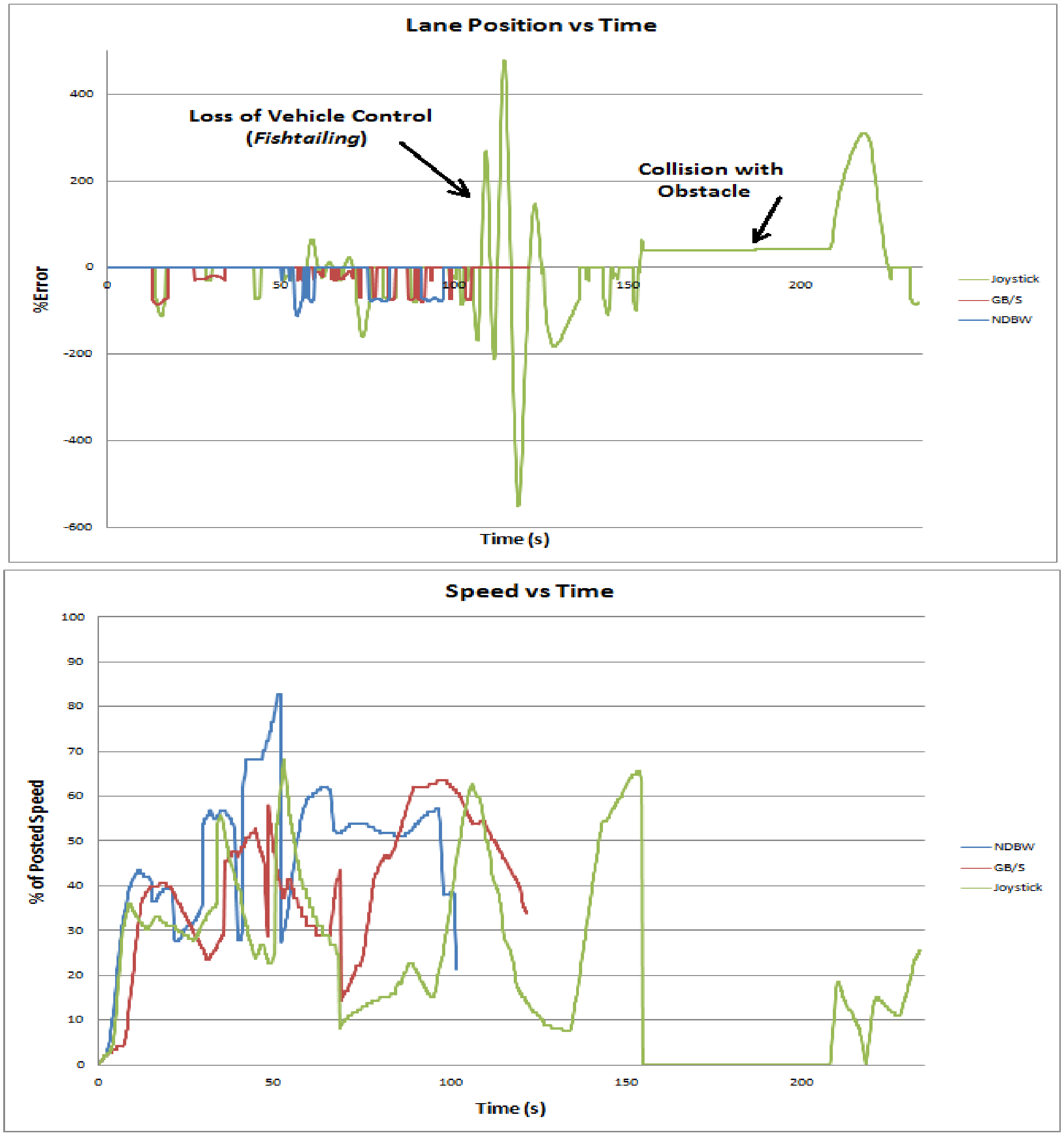


Figure 7.5 - Common Steering Mistakes

Common steering errors committed in the steering test can easily be seen in the graphs shown in Figure 7.5 from 105-140 seconds and from 150-210 seconds. In the first time frame, an oscillatory wave shows a loss of vehicle control. As the driver makes a correction to steer the vehicle back into the lane, he or she holds the wheel position too long and must then sharply steer to the other direction to counteract the oversteering mistake. At some point, if the driver either makes a correction too sharply or if vehicle speed is not reduced, the vehicle begins to fishtail. In this case, as the driver began to lose control, he applied the brake to slow the vehicle and was able to regain control. Secondly, in the second time frame, the lane position becomes constant. This alone does not necessarily represent an error. However, when this is accompanied by a nearly instantaneous change in vehicle speed to zero miles per hour, it shows that the vehicle has crashed into an obstacle.

A full set of position and velocity graphs for all 30 participants can be found in Appendices C.2 – C.4. A sample of the discrete data points taken at 0.2 seconds intervals can also be found in C.2.

7.3 Evaluation of Drivers in Traffic

The traffic driving tests were another method for determining how participants drove and were able to understand the control of each of the driving systems. For all participant groups, the time spent driving in the city route was significantly longer than the time spent on the highway. For this reason, it was necessary to normalize the errors with respect to time. Tables 7.4 and 7.5 show the total number of errors (x- number of instances; s- duration in seconds), error rate, and the percentage of the total driving time that errors were being committed. A more detailed list of error totals, including individual types of errors can be found in Appendix C.5. An explanation of these errors can be found in Appendix B.

On route "A," all groups of drivers committed the most errors when using the joystick system. The majority of these errors came from the inability to maintain lane position. It was evident from the steering tests that the joystick controller was the most difficult to maintain a straight heading with. It is interesting to note that for Group 1 drivers in the city, fewer mistakes per minute occurred with the use of the GB/S system, despite having little training with it. Elderly drivers followed suit, having an error rate of 4.8 per minute using the GB/S system while demonstrating an error rate of 5.33 instances per minute with the NBDW system. Nevertheless, while error rates were lower in elderly drivers, the duration of the time that these errors were being committed was 3.32% higher. This means that with the GB/S system, elderly drivers were not easily able to quickly correct errors.

Table 7.4 - Route "A" Error Totals

Route "A"	NDBW	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	3258	227	294	4.18	9.02
	65+	2995	266	326	5.33	10.88
	Disability	n/a	n/a	n/a	n/a	n/a
	GB/S	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	3356	222	239	3.97	7.12
	65+	3478	278	494	4.80	14.20
	Disability	3247	281	404	5.19	12.44
	Joystick	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	3153	323	507	6.15	16.08
	65+	2863	378	495	7.92	17.29
	Disability	3463	350	544	6.06	15.71

Table 7.5 - Route "E" Error Totals

Route "E"	NDBW	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	1722	123	116	4.29	6.74
	65+	1827	180	195	5.91	10.67
	Disability	n/a	n/a	n/a	n/a	n/a
	GB/S	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	2083	171	233	4.93	11.19
	65+	1879	228	300	7.28	15.97
	Disability	1679	149	187	5.32	11.14
	Joystick	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	2124	433	528	12.23	24.86
	65+	2120	350	611	9.91	28.82
	Disability	1437	283	384	11.82	26.72

From Table 7.5, drivers on route "E" made the most errors again while using the joystick. For Group 1, 6.7% of the time was spent commiting errors with the NDBW system, 11.2% with the GB/S system, and 24.9% of the time using the joystick. For Group 2, percent of the time committing errors was 10.7%, 16.0%, and 28.8% for the NDBW, GB/S, and joystick systems respectively. In group 3, drivers had some real world experience using either mechanical hand controls or DBW control systems. The error rate for this group was 222% higher when using the joystick (5.32 errors/min versus 11.82 errors/minute). Group 2 drivers on the joystick systems, had the lowest error rate (9.9 errors/minute) among the other groups, yet, the percent of the total time spend committing errors was the highest at 28.8%. This indicates that elderly drivers have the most difficult time correcting errors quickly.

A review of the total error rates for both routes shows that there is little difference in the performance of Group 1 and 2 drivers when using the NDBW or GB/S systems. At the same time, these participants committed 3-4 more errors per minute when using the joystick. For Group1, the total time spent committing errors was approximately 11% higher when using the joystick versus the NBDW or the GB/S system. With all three systems, elderly drivers were the slowest to correct their mistakes. Drivers with disabilities as a whole performed the best among the three groups when using the joystick. They committed nearly 1 error less per minute on average. The time they spent committing these errors was 0.67% shorter than able-bodied participants and 3.26% less than elderly drivers.

Table 7.6 – Traffic Tests Error Totals

		Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
Total	**NDBW**	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	4980	350	410	4.22	8.23
	65+	4822	446	521	5.55	10.80
	Disability	n/a	n/a	n/a	n/a	n/a
	GB/S	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	5439	393	472	4.34	8.68
	65+	5357	506	794	5.67	14.82
	Disability	4926	430	591	5.24	12.00
	Joystick	Total Time	Errors (x)	Errors (s)	Error Rate (x/min)	% Error Time
	18-64	5277	751	1035	8.54	19.61
	65+	4983	724	1106	8.72	22.20
	Disability	4900	631	928	7.73	18.94

7.4 Driving Performance Survey

Following each of the tests, subjects were asked a series of questions pertaining to their thoughts about each system. The averages of their quantitative responses after completing all of the tests are tabulated in Table 7.7. The complete responses table can be found in Appendix F. In the table a response of 1 indicates unreliable, very difficult, etc.. A response of 5 represents very reliable, very easy, etc..

Table 7.7 – Average Quantitative Survey Results

	Group 1	Group 2	Group 3
GB/S	AVG	AVG	AVG
Ease of Learning:	3.9	3.1	4.5
Proficiency:	4.3	4.2	4.4
Ease of Operating System:	3.8	2.8	4.6
System Safety	3.3	2.8	3.6
Confidence:	3.7	2.5	4.4
System Reliability:	3.9	4	4.2
Realism of Scenarios:	4	3.6	4.3
Joystick	AVG	AVG	AVG
Ease of Learning:	2.7	1.9	2.8
Proficiency:	3.2	2.6	3.4
Ease of Operating System:	3.2	1.7	3.2
System Safety	2.2	2.1	2.2
Confidence:	2.4	1.8	2.9
System Reliability:	3	3.5	3.2
Realism of Scenarios:	3.9	3.2	4
W/out DBW	AVG	AVG	AVG
Ease of Learning:	4.5	3.4	
Proficiency:	4.4	4.4	
Ease of Operating System:	4.5	3.5	
System Safety	4.2	3.2	
Confidence:	4.5	3.1	
System Reliability:	4.3	3.8	
Realism of Scenarios:	3.8	3.6	

Table 7.8 - Standard Deviation of Survey Responses

	Group 1	Group 2	Group 3
GB/S	AVG	AVG	AVG
Ease of Learning:	0.567646	1.054093	0.707107
Proficiency:	0.674949	0.971825	0.516398
Ease of Operating System:	0.421637	1.20185	0.699206
System Safety	0.823273	1.658312	1.173788
Confidence:	0.483046	1.236033	0.699206
System Reliability:	1.100505	1.054093	1.229273
Realism of Scenarios:	0.942809	1.740051	0.483046
Joystick	AVG	AVG	AVG
Ease of Learning:	1.159502	1.581139	0.918937
Proficiency:	0.788811	1.236033	1.349897
Ease of Operating System:	1.316561	0.971825	1.229273
System Safety	1.135292	1.364225	1.229273
Confidence:	0.843274	1.364225	1.286684
System Reliability:	1.054093	1.130388	1.032796
Realism of Scenarios:	0.875595	1.536591	0.471405
W/out DBW	AVG	AVG	AVG
Ease of Learning:	0.707107	1.130388	
Proficiency:	0.843274	0.726483	
Ease of Operating System:	0.707107	1.130388	
System Safety	1.032796	1.658312	
Confidence:	0.707107	1.481366	
System Reliability:	0.674949	1.224745	
Realism of Scenarios:	1.135292	1.236033	

Drivers in both Group 1 and 2 felt that the NDBW system was the easiest to learn, easiest to operate, safest and most reliable. They also felt that while using this system, they were most proficient and confident. The joystick system was the most difficult to learn, most difficult to operate, most unsafe, and least reliable according to their responses. In a similar fashion, drivers with disabilities felt that the GB/S system was easier to learn, easier to operate, safer, and more reliable than the joystick system. All drivers agreed that the system gave them realistic scenarios of driving.

After administering the acceleration and braking test to all 30 individuals from each of the three test groups it was found that, in general, individuals between the ages 18-64 performed better than the elderly group for each of the three systems. This generalization is made based on the fact that a higher maximum vehicle speed constitutes a better control of the acceleration interface. Furthermore, the test not only requires the subject to follow onscreen commands for stopping, he or she must also maintain a straight vehicle heading as there are boundaries in the virtual environment to either side. The user must actively think about how to correct an error in heading. Therefore, some of the user's free cognitive ability is impeded by this interference. Despite the well known fact that, in most cases, as age increases, so does reaction time, a longer reaction time might suggest that the individual does not have adequate control of the vehicle and must actively concentrate on steering at the same time. When driving in traffic and using the joystick system, drivers with disabilities made fewer errors than the other two groups.

All of the user groups, on average, exhibited a shorter reaction time to applying the brake when being issued a visual stop command while using GB/S controls. In the acceleration and braking tests, Group 1 drivers had only slightly better reaction times when using the joystick over the standard vehicle controls. Elderly drivers had nearly identical reaction times when using the standard vehicle controls or the joystick system.

When the driver applies the brake, he or she must pick up the foot, move it over the brake, and then begin applying the brakes. When using the DBW controls, the driver simply has to move the wrist a slight distance without physically becoming disconnected from the interface. This alone shortens their reaction time. However, presently, the servo motor must mechanically take the place of the foot, applying the gas or brake. This took more time than the driver took to transfer the foot to the other pedal. Consequently, stopping distances were longer when using DBW system in the simulator.

The joystick is a type of coupled system in which the gas/brake and steering inputs are integrated on the same controller. For this reason, many users found it difficult to control acceleration functions independently from the steering functions. When a driver was trying to correct lane position using the joystick, often times, he or she would apply maximum acceleration or let go or the stick to return it to center and then make the steering correction instead of maintain the proper forward acceleration angle on the joystick and making the steering correction at the same time. In fact, nearly all of the participants felt that the GB/S system was easier to control because the inputs were on separate controllers. The results of the performance tests confirm this feeling conveyed by the study participants. With the GB/S system there were fewer errors and drivers were able to complete the scenarios in less time, which indicates that the maximum vehicle speed was higher and there were fewer obstacle collisions.

Chapter 8: Conclusions

From the results in the previous chapter, it can be seen that, of the two DBW driving systems, the AEVIT joystick is the most difficult to master. While errors were common for drivers using the DBW GB/S steering system, they were nearly twice as common with the joystick system. In the steering test, elderly drivers had a relative error as high as 81% when using the joystick system.

Since route “A” consisted of a greater number of turns than route “E,” it was expected that more errors would occur in that environment. However, a far greater number of errors were incurred when the driver was driving on the highway. In that environment (route “E”) drivers were constantly required to adjust the steering wheel angle to maintain their lane position. Error rates were lower in the city partly because much of the drivers’ time was spent waiting at red stop lights.

From the results in this study, it was not possible to quantitatively determine if there was a difference in the learning curve between the user groups for any of the control systems. More specific tests need to be designed to further investigate the matter. With that said, driver tended to show improvement as the testing progressed. Some also stated that they felt more comfortable with the controls at the end of the testing versus at the beginning.

When participants were driving through the city and highway routes, they were asked to maintain safe driving practices. This included the use of turn signals, and checking mirrors before making lane adjustments. While driving with the GB/S system drivers had to remove one of their hands from either the gas/brake controller or the small steering wheel. Some decided to remove their hand from the steering controller on the right and reach over the steering column to engage the turn signal rather than using the left hand to operate the signal. The latter was the safer choice as the time that the hand was removed from the controller was shorter. Additionally, many drivers safely coast without acceleration or braking input before making a turn. Essentially, that is what happens when the gas-brake lever is returned to the neutral position.

When drivers were asked about how they perceived the system, a variety of responses ensued. Repeatedly, drivers felt that the joystick system was “sluggish” and they were unable to correct steering mistakes. They also stated that it was nearly impossible to keep the vehicle on a straight path for any length of time. Furthermore, it was iterated more than once that the joystick would take much more time to learn but that it could be done, given enough time and training. Most drivers felt that the acceleration and braking controls for all of the three systems were adequate and fairly easy to control.

In conclusion, a simulator utilizing DBW control systems can be an effective training tool for drivers with disabilities. In most cases, able-bodied person who were capable of driving with the standard pedal and steering wheel were happy to continue using that system rather than having to learn a new DBW system. This was particularly true for the elderly drivers. The only apparent benefit of using DBW control systems for elderly drivers and individuals without disability was a reduced reaction time. Additionally, it could be helpful for the elderly who do not have the strength or dexterity required to rotate a standard steering wheel. However, the shortened reaction times were diminished by the extended time for the servo to actuate the gas or brake pedals. More information is needed to develop a useful program that can be used for training with DBW controls in lieu of the somewhat unsafe real world training. From this study however, it is evident that training with the joystick requires much more practice for proficiency over the GB/S controls. In this study eight persons with a disability used mechanical controls in their personal vehicles whereas 2 used DBW systems.

Some drivers stated that the system appeared to be somewhat sluggish. In fact, however, the system was extremely responsive, having a response time for steering of less than 0.03 seconds. Participants were oversteering and consequently, felt as if they were unable to quickly control the vehicle. This happened particularly often with the elderly participants.

The results show that in a future training lab, the drive by wire joystick would require a significantly larger amount of training time versus the GB/S system. This is evidenced by the fact that most drivers did poorly with the joystick and even stated that the system was much more difficult and less reliable than the other systems. Most simulators include a training program that evaluates a students' level of proficiency. This could be used to asses the amount of training that may still be required. Furthermore, some of the drivers were left-handed but were asked to used the controls with theh right hand so that the number of uncontrolled variables could be limited. For training, drivers should be allowed to use their dominate hand. Secondary controls, not used in this study, need to be implemented for realism and ease of use. The same holds true for orthotic devices.

Chapter 9: Future Work

9.1 Development of a New Drive-by-Wire Controller

This study lays the groundwork for a further study related to the development of a new DBW controller. Currently modified vehicles with adaptive driving equipment require extensive modifications and the cost is extravagantly high. A new type of system could be developed so that it is self-contained and portable. A plug-and-play interface would allow the controller to be used in more than one vehicle, even allowing a driver to utilize a rented automobile, a common limitation that inhibits some freedom for drivers with disabilities. The controller could interface with an assistive steering and acceleration/braking computer to provide the terminal locomotion necessary for vehicle control. Ideally, this new type of system would provide, for those who require it, a less expensive and more efficient means of vehicle modification.

The development of a new state-of-the-art DBW of controller would necessitate a human-factors study to further understand what is necessary in DBW controller design to facilitate adequate vehicle control. Information from this study could be used to supplement this further investigation.

9.2 Development of an Immersive Environment

According to Witmer and Singer, in order for a virtual environment to be the most effective, it must give the sense of presence, a concept not realized until both involvement and immersion coexist [9]. Involvement happens when a subject is interested in t he task and enjoys the experience of driving in a virtual environment. The USF driving simulator, despite being captivating for users, cannot be an effective training tool until immersion is developed.

It is necessary to exclude the surrounding environment from the driver, as this presents a number of distractions, detracting from the realism. The screen in the simulator is also somewhat small and the field of view is limited to what normally can be seen from the windshield. Peripheral vision in the vehicle is nonexistent. A curved screen with at least a 180 degree arc would allow drivers to feel more involved and to make faster gains from a training perspective.

Additionally, the current simulator lacks a form of dynamic feedback. Dynamic feedback would improve a driver's ability to understand mistakes and relate them to the real world more effectively. This could be implemented at the control interface so that a driver could "feel" the edge of the road through a DBW controller. Additionally, an enhanced sensation of realism could be developed by the implementation of a dynamic platform. The van shell and screen could be mounted to the platform and would move in accordance with the control input from the driver.

9.3 Driver Training Program

Another eventual goal future related projects is to develop a low-cost driver training program that can be used to train individuals to drive with DBW systems before actually doing so on the road. Further study must be conducted to determine what constitutes enough training for proficiency with DBW controls, although the results of this study demonstrate that the joystick system is much more difficult . To investigate the requirements for adequate driving control in an virtual environment, an individual could be trained in a simulator and then demonstrate their proficiency in a real vehicle. Their performance should be compared to a control group that trains solely in a modified vehicle. State-approved guidelines for proficiency with adaptive driving equipment should be applied.

Additionally, careful attention should be given to the positive and negative trends in the transfer of training from a simulated environment to the real world. It would seem that training with the joystick system would require much more practice and training than for the GB/S system. Furthermore, the simulator should be expanded so that training with mechanical controls is possible, since the majority of adaptive equipment installed in vehicles is of this type.

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Appendices

Appendix A: Boot-Up Procedures

A.1 SSI Simulator

1. Verify that the power cord from the SSI computer is plugged in.
2. Place the SSI Power Switch in the "-" position (Fig. A.1)

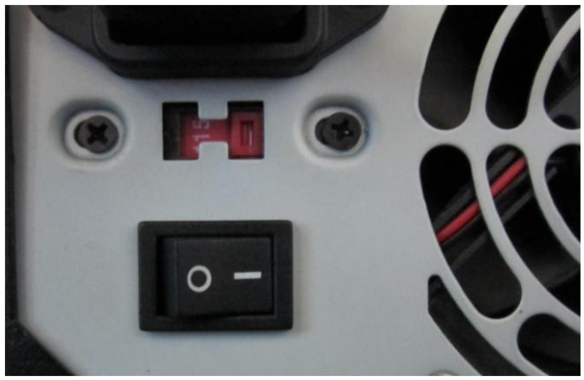


Figure A.1 - SSI Power Switch

3. Push the red SSI Power Button (Fig. A.2) The rear cooling fan should turn on and the green light in the center of the red button will shine.

Figure A.2 - SSI Power Button

4. Once the operating system has loaded and the SSI Simulator program is ready, tap the touchpad or click an installed USB mouse to begin.
5. Enter the correct username and password.

Appendix A: (Continued)

A.1.1. SSI Menu Navigation

Figure A.3 - SSI Main Menu

1. The Main Menu (Fig. A.3) appears after the correct username and password had been entered. The brake calibration, acceleration and braking tests, steering tests, and routes "A" and "E" can be accessed from here.

Calibration of Brake (for all control systems)

1. Click on "Other" from the Main Menu Screen.
2. Click on "Maintenance"

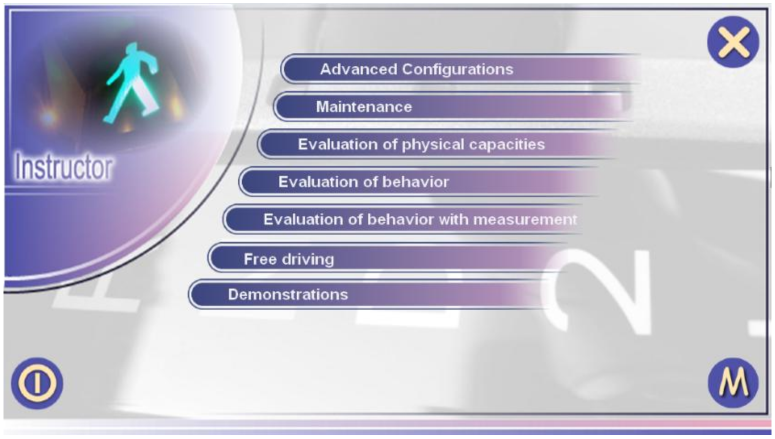


Figure A.4 - "Other" Screen

Appendix A: (Continued)

3. Click on “Settings.”

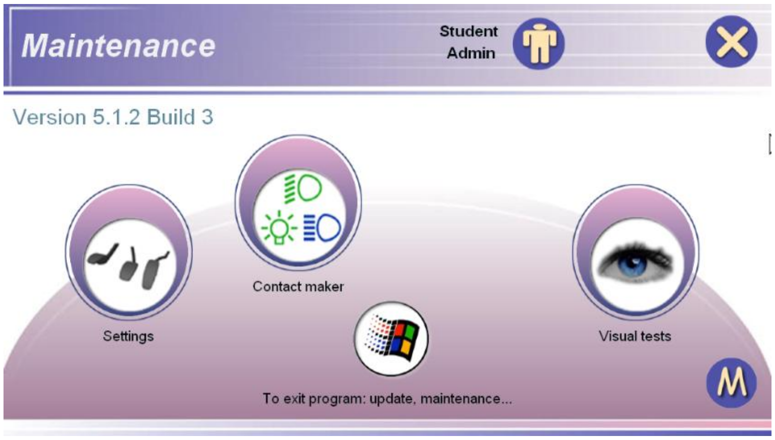


Figure A.5 – SSI Maintenance Screen

4. Click on “Brake.”

Figure A.6 - SSI Calibration Screen

5. Depress the brake fully and click on the "Next" button while applying the brake.

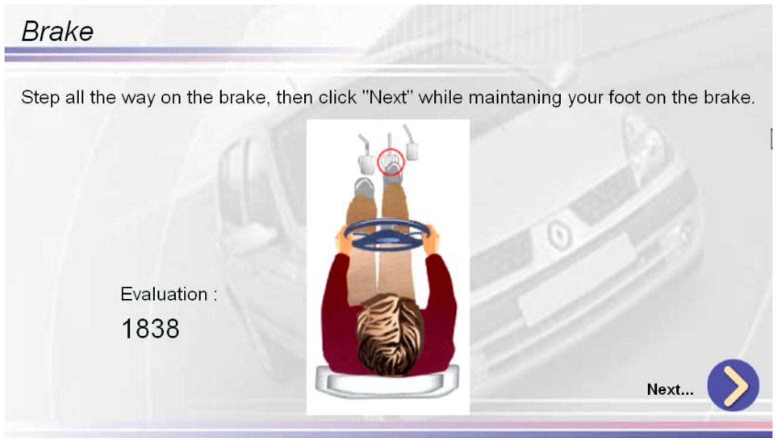


Figure A.7 - SSI Brake Calibration Screen 1

6. Let go of the brake. Click "Next."

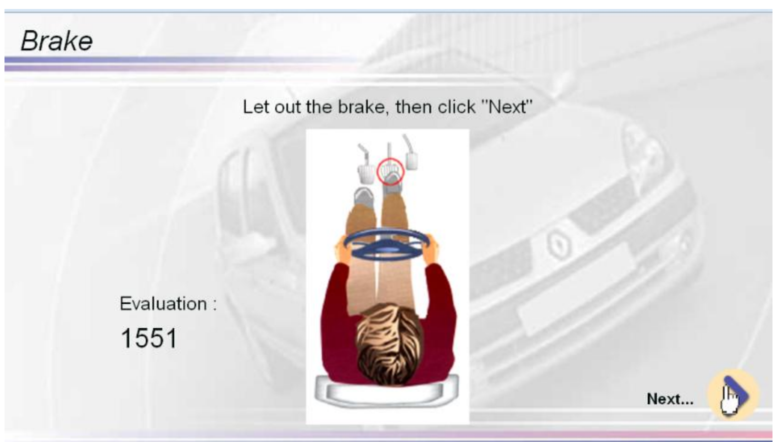


Figure A.8 - SSI Brake Calibration Screen 2

Appendix A: (Continued)

7. Verify that full application of the brake causes the slider to move all the way up and down.

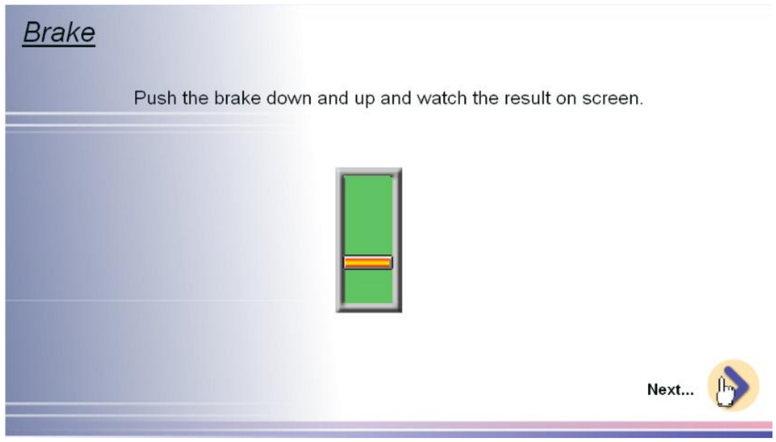


Figure A.9 - SSI Brake Calibration Screen 3

8. Click on "Menu" to return to the previous menu.

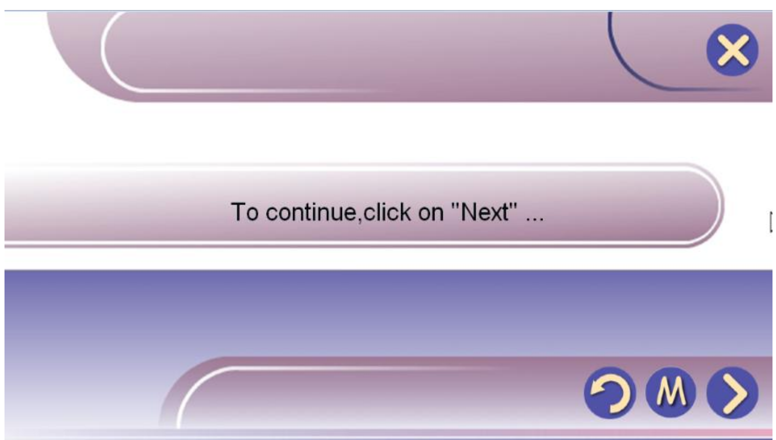


Figure A.10 - SSI Main Menu Return Screen

Appendix A: (Continued)

Acceleration and Braking Test

1. From the main menu, click on "Other."
2. Click on "Evaluation of Physical Capacities" (Fig. A.4).
3. Click on "Motor Skills."

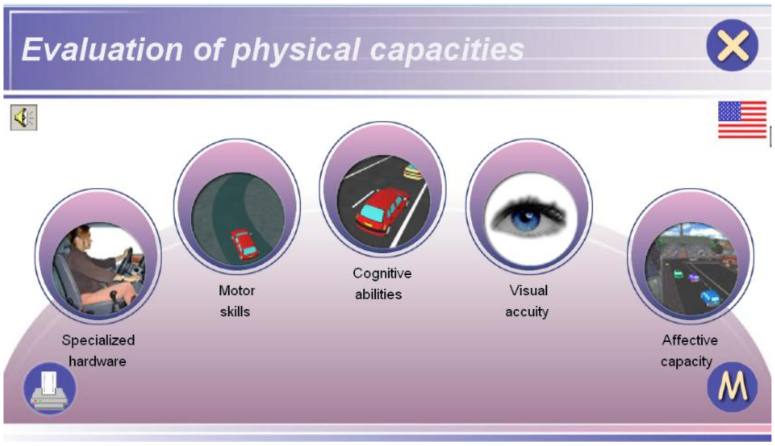


Figure A.11 - SSI Evaluation of Physical Capacities Screen

4. Click on "Reaction time to applying the brake."

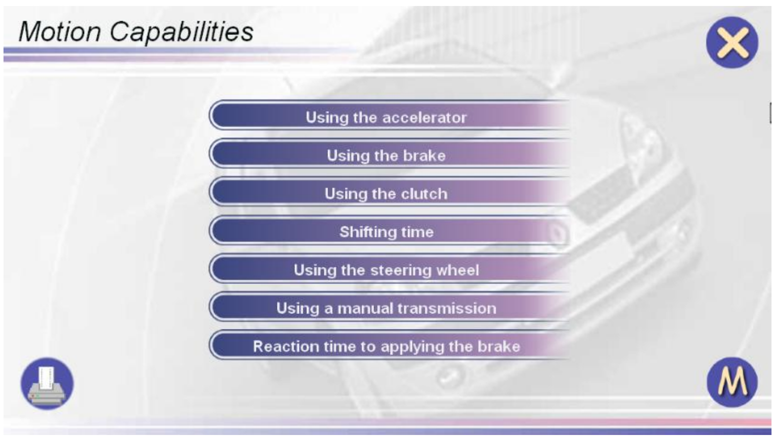


Figure A.12 - SSI Motor Skills Screen

Appendix A: (Continued)

5. Click on "Next" to begin the test.

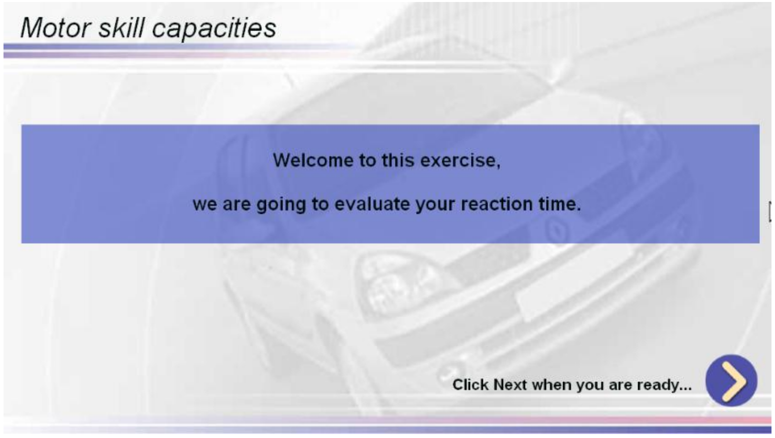


Figure A.13 - SSI Reaction Time Test Screen

Steering Test

1. From the main menu, click on "Other."
2. Click on "Evaluation of Behavior with Measurement" (Fig. A.4).
3. Click on "Winding Driving with Variable Speed."

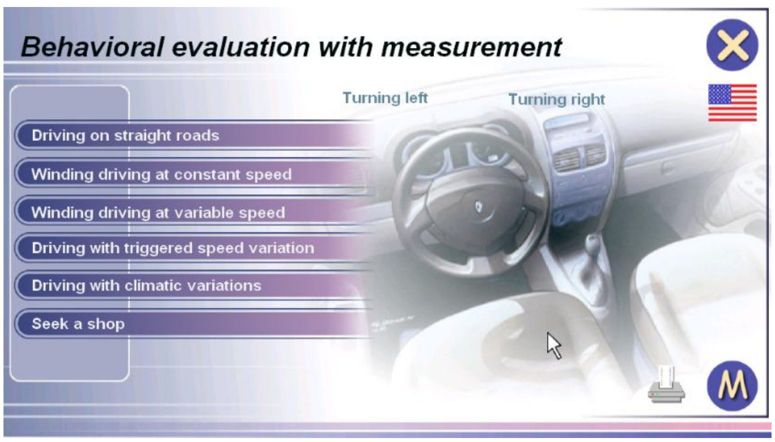


Figure A.14 - SSI Behavioral Evaluation with Measurement Screen

Appendix A: (Continued)

Routes "A" and "E"

1. From the main menu click on "Advanced Training" (Fig. A.3).

2. Click on "Practice Driving."

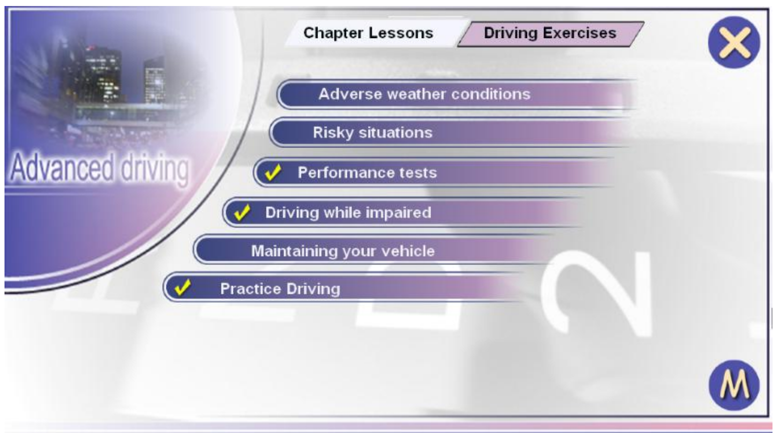


Figure A.15 - SSI Practice Driving Screen

3. Click on "City" to get to the scenario setup screen.

Figure A.16 - SSI City Routes Screen

Appendix A: (Continued)

A.2. Boot-up Procedure for AEVIT Simulator

1. Engage the red blade switch to connect the battery to the SSI system.

The order in which the system is turned on is very important. As a rule turn the rocker switches on from left to right and always leave the "Engage" switch turned on.

Buttons on AEVIT Simulator module from left to right:

1. "Simulator power": turn on first
2. "Ignition": turn on second
3. "Engage": leave on at all times
4. "Brake lights": turn on third, (when on, system will not shut down by its own)
5. "Parking lights": leave off at all times, (doesn't have any effect on system)
6. "Speed signal": turn on fourth, (knob under switch does not seem to have any effect on system)
7. "Coil pulses": turn on fifth, (even when on system displays error "no coil pulses present", knob under switch does not seem to have any effect on system)
8. "Remote off switch"

After the AEVIT system has booted, it will require calibration. The instructions can be found in Appendix A.3.

To power off the AEVIT system, on the simulator module:

1. Turn off "Ignition."
2. Turn off "Simulator Power."

Appendix A: (Continued)

3. Press and hold “Remote off switch” or “System OFF” on the Information Center (Fig A.19).

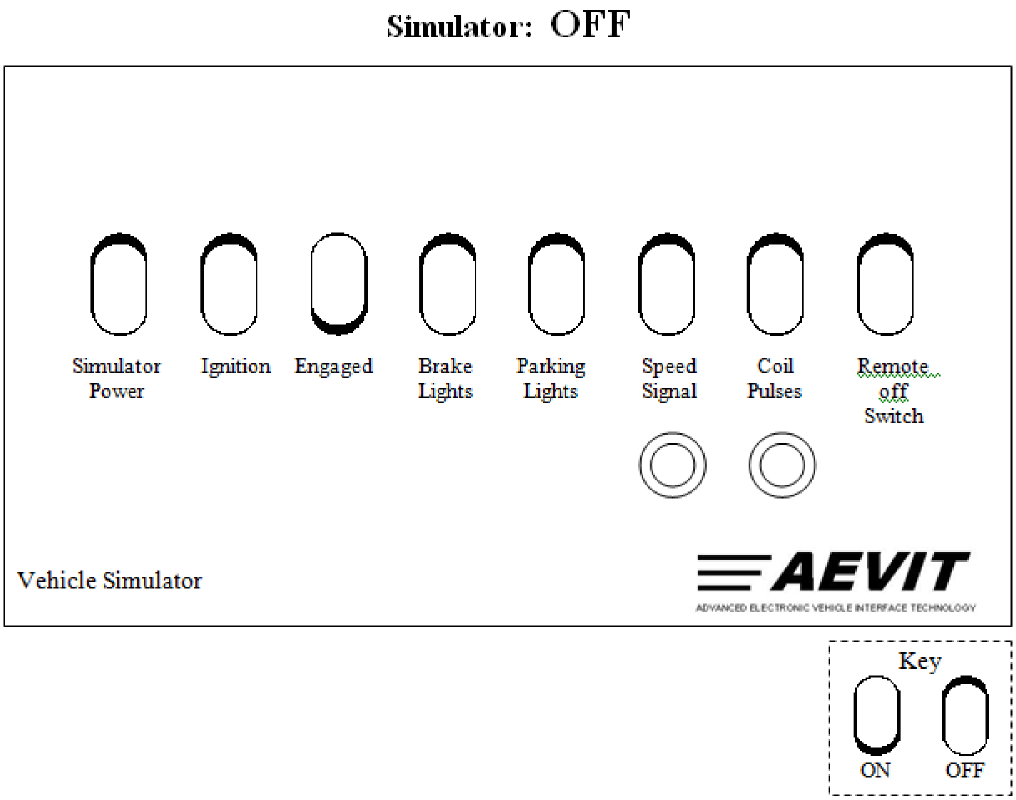


Figure A.17 - AEVIT Vehicle Simulator OFF position

Appendix A: (Continued)

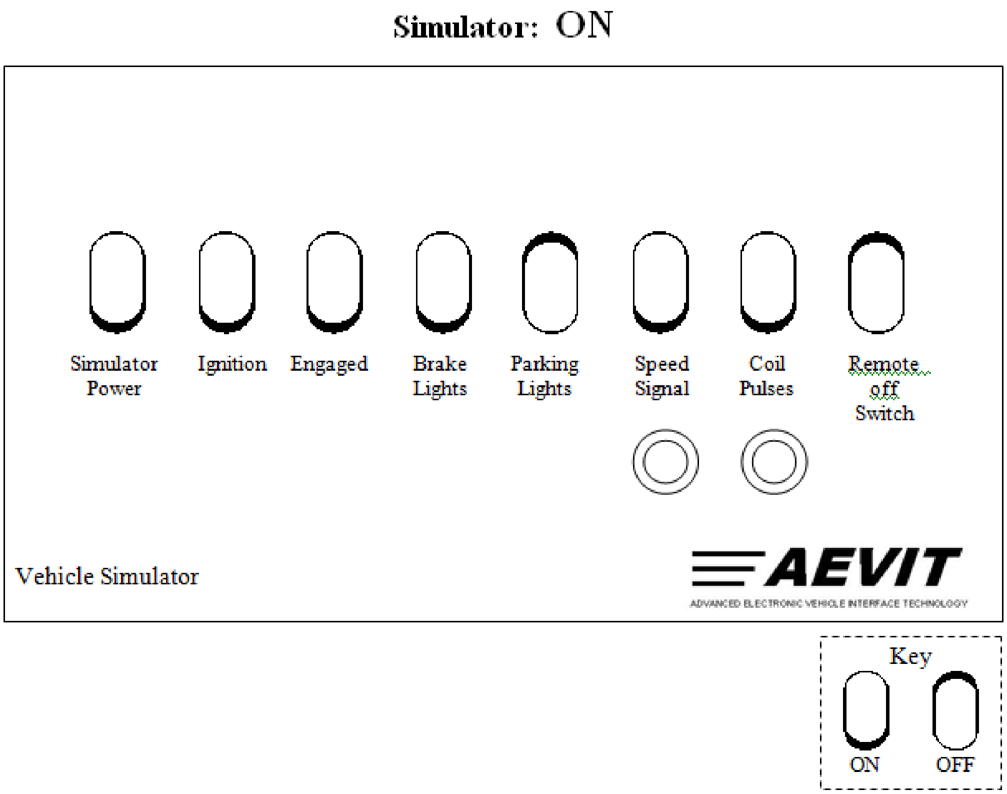


Figure A.18 - AEVIT Simulator Module ON Position

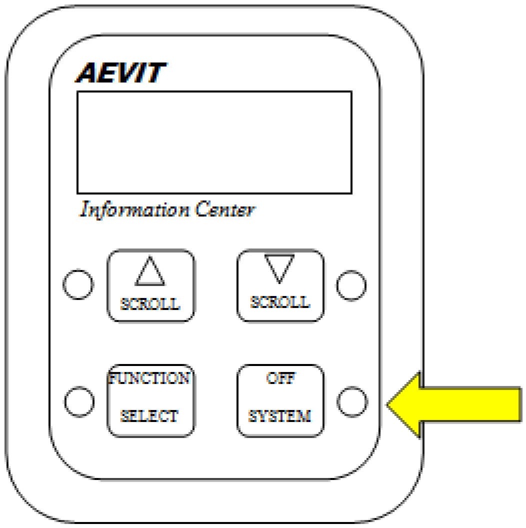


Figure A.19 - AEVIT Information Center Off Switch

Appendix A: (Continued)

A.3 Calibration of AEVIT Controllers

Boot-Up Procedure (4-axis joystick)

1. Verify that *A* has been selected on the black switch box.
2. Connect Power supply cord. Be sure that the power supply is turned on and that the alligator clips are connected to the battery.
3. Throw the switches on the AEVIT Vehicle Simulator Module labeled, *Simulator Power* and *Ignition*.
4. The AEVIT Information Center will then display the following message:

Warning: Steering

Type Changed to

4-Axis Joystick

SELECT to Confirm

Press *Function/Select* button.

5. The AEVIT Information Center will then display the following message:

Warning: Gas/Brake

Type Changed to

2-Axis Joystick

SELECT to Confirm

Press *Function/Select* button.

6. The AEVIT Information Center will then display the following message:

Gas Brake Not Booted

Manually Test Drive

Side 1: *Waiting*

Side 2: *Waiting*

Push the joystick forward and rearward until both sides read *Booted*.

7. The AEVIT Information Center will then display the following message:

Steering Not Booted

Manually Test Drive

Side 1: *Waiting*

Side 2: *Waiting*

Push the joystick left and right until both sides read *Booted*.

8. Verify that the servo motor is engaged. If not, center the SSI steering wheel and rotate the *engage lever* and secure with the locking pin.

Boot-Up Procedure (Steering Wheel and Gas/Brake Lever)

1. Verify that *B* has been selected on the black switch box.

2. Connect Power supply cord. Be sure that the power supply is turned on and that the alligator clips are connected to the battery.
3. Throw the switches on the AEVIT Vehicle Simulator Module labeled, *Simulator Power* and *Ignition*.
4. The AEVIT Information Center will then display the following message:

Warning: Steering

Type Changed to

WHEEL

SELECT to Confirm

Press *Function/Select* button.

5. The AEVIT Information Center will then display the following message:

Steering system not aligned

Rotate the small steering wheel so that the arrows align and the warning goes away.

6. The AEVIT Information Center will then display the following message:

Warning: Gas/Brake

Type Changed to

LEVER

SELECT to Confirm

Press *Function/Select* button.

7. The AEVIT Information Center will then display the following message:

Gas Brake Not Booted

Manually Test Drive

Side 1: *Waiting*

Side 2: *Waiting*

Press the gas/brake lever forward and rearward until both sides read *Booted*.

8. The AEVIT Information Center will then display the following message:

Steering Not Booted

Manually Test Drive

Side 1: *Waiting*

Side 2: *Waiting*

Rotate the gas/brake lever forward and rearward until both sides read *Booted*.

9. Verify that the servo motor is engaged. If not, center the SSI steering wheel and rotate the *engage lever* and secure with the locking pin.

Appendix B: Types of SSI Driver Errors

While testing on routes “A” and “E”, drivers were flagged for committing traffic offenses. The figures below show each offense in progress.

1. Traffic Collision – The driver strikes another vehicle
2. Dangerous Intersection Crossing – The driver goes through an intersection controlled by a red light
3. Speeding Infraction – The driver is exceeding the speed limit by more than 5 mph
4. Improper Lane Position – The driver is drifting out of the lane
5. Inadequate Space Cushion – The driver is unsafely following the vehicle in front
6. Turn Signal Missed – The driver failed to signal before making a turn or changing lanes

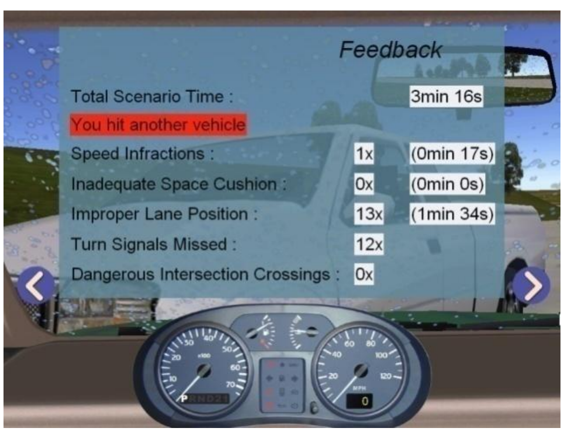


Figure B.1 - Traffic Collision

Figure B.2 - Dangerous Intersection Crossing

Appendix B: (Continued)

Figure B.3 - Speeding Infraction

Figure B.4 - Improper Lane Position

Figure B.5 - Inadequate Space Cushion

Figure B.6 - Turn Signal Missed

Appendix C: Human Subject Testing Data

C.1 Acceleration and Braking

The following tables include data for each of the three systems for each participant:

Table C.1 - NDBW Acceleration/Braking Data

Group 1	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
1	57.5	0.668	0.5	176.13	179.00	51.27	38.37	124.93	140.27
2	57.6	0.867	0.5	195.23	179.00	66.57	38.37	128.67	140.50
3	57.5	0.790	0.5	188.13	178.67	60.57	38.30	127.57	140.13
4	55.7	1.337	0.5	224.87	169.33	99.43	37.23	125.43	132.27
5	54.8	0.668	0.5	160.70	164.33	48.73	36.50	111.97	127.67
6	57.5	0.634	0.5	173.30	179.00	48.60	38.40	124.67	140.47
7	57.5	0.790	0.5	186.40	179.00	60.63	38.37	125.80	140.50
8	56.4	0.668	0.5	170.63	172.67	50.30	37.63	120.30	135.20
9	56.6	0.891	0.5	191.00	173.67	67.20	37.73	123.80	135.93
10	54.6	0.568	0.5	155.43	162.33	41.33	36.37	114.07	126.40
Group 2	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
11	53.9	0.892	0.5	174.27	159.33	64.17	35.97	110.10	123.37
12	53.0	0.891	0.5	166.70	154.67	63.10	35.37	103.60	119.37
13	53.3	0.613	0.5	159.23	156.00	43.60	35.53	115.60	120.60
14	53.2	0.635	0.5	145.83	155.33	45.00	35.43	100.80	119.97
15	56.6	0.880	0.5	191.57	173.67	66.47	37.73	125.10	136.13
16	56.5	1.048	0.5	201.33	173.33	78.87	37.67	122.47	135.60
17	57.0	0.491	0.5	163.33	176.33	37.30	38.03	126.00	138.03
18	57.6	0.703	0.5	186.03	179.00	53.80	38.37	132.20	140.50
19	57.5	0.790	0.5	186.80	179.00	60.60	38.37	126.20	140.47
20	52	1.315	0.5	193.33	149	91.53	34.63	101.8	116.53
Group 3	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
22	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
23	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
24	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
25	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
26	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
27	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
28	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
29	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
30	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Appendix C: (Continued)

Table C.2 - GB/S Acceleration/Braking Data

18-64	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
1	57.5	1.303	0.5	232.53	178.67	99.93	38.37	132.63	140.37
2	57.5	1.112	0.5	217.43	179.00	85.40	38.37	132.03	140.40
3	57.6	1.046	0.5	210.50	179.00	80.27	38.40	130.20	140.53
4	54.8	1.214	0.5	208.63	164.33	88.47	36.53	120.13	127.83
5	56.4	0.914	0.5	193.00	172.67	68.90	37.60	124.13	135.23
6	57.5	0.957	0.5	203.07	179.00	73.43	38.37	129.60	140.43
7	57.6	0.912	0.5	199.80	179.00	70.00	38.40	129.77	140.53
8	54.6	0.813	0.5	175.67	163.33	59.30	36.43	116.40	126.73
9	56.2	1.192	0.5	214.63	171.67	89.47	37.47	125.20	133.97
10	56.5	1.204	0.5	221.13	172.67	90.63	37.63	130.50	135.33
65+	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
11	57.2	1.459	0.5	243.87	177.00	111.33	38.10	132.60	138.73
12	56.4	1.092	0.5	208.77	172.33	82.20	37.60	126.53	135.00
13	56.2	1.003	0.5	198.93	172.00	75.33	37.50	123.63	134.30
14	53.4	1.248	0.5	199.53	157.00	88.43	35.60	111.10	121.30
15	53.7	1.204	0.5	200.60	158.67	86.53	35.80	114.10	122.70
16	54.4	1.293	0.5	209.93	162.00	94.33	36.23	116.17	125.57
17	55.3	0.981	0.5	190.87	167.00	71.97	36.90	118.93	130.30
18	57.6	1.192	0.5	226.57	179.00	91.43	38.57	135.13	140.63
19	57.5	1.482	0.5	248.77	179.00	113.63	38.33	135.13	140.33
20	56.1	1.214	0.5	217.03	171	90.80	37.43	125.93	133.63
Disability	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
21	56.3	0.892	0.5	190.50	172.33	67.13	37.57	123.37	134.73
22	56.7	0.936	0.5	196.63	174.67	70.93	37.83	125.70	136.63
23	54.3	1.137	0.5	197.37	161.67	82.30	36.10	115.03	125.53
24	56.2	1.047	0.5	211.37	171.33	78.23	37.50	133.13	134.13
25	55.4	0.980	0.5	191.63	167.33	72.53	36.93	119.10	130.33
26	57.5	0.991	0.5	206.50	179.00	76.00	38.37	130.50	140.40
27	57.6	1.085	0.5	214.33	179.00	83.27	38.40	131.07	140.53
28	56.7	1.416	0.5	236.27	174.67	107.03	37.80	129.20	136.50
29	57.5	1.314	0.5	228.73	179.00	100.83	38.37	127.90	140.47
30	56.8	1.104	0.5	212.03	175.00	83.63	37.93	128.40	137.13

Appendix C: (Continued)

Table C.3 - Joystick Acceleration/Braking Data

18-64	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
1	57.4	1.335	0.5	232.10	178.00	100.67	38.27	131.43	139.80
2	57.5	1.471	0.5	247.33	178.67	112.73	38.30	134.60	140.27
3	55.4	0.970	0.5	188.97	167.33	71.80	36.97	132.17	130.27
4	56.4	1.326	0.5	226.23	173.00	99.80	37.63	126.43	135.30
5	53.9	1.115	0.5	193.67	159.67	80.07	35.87	113.60	123.47
6	57.5	1.057	0.5	211.50	179.00	81.03	38.33	133.80	140.33
7	56.1	1.203	0.5	214.40	171.00	90.00	37.43	124.40	133.73
8	57.1	0.958	0.5	199.63	176.33	72.90	38.07	126.70	138.10
9	56.6	1.036	0.5	204.43	173.67	78.23	37.77	126.17	135.93
10	56.5	1.204	0.5	231.93	172.67	102.30	37.63	129.60	135.23
65+	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
11	57.4	1.292	0.5	232.10	178.67	98.97	38.30	133.17	140.07
12	54.0	0.853	0.5	170.60	160.00	61.80	36.00	108.75	123.90
13	57.1	1.158	0.5	217.23	176.00	88.13	38.00	129.13	138.00
14	55.0	0.992	0.5	185.57	165.00	72.90	36.63	112.70	128.23
15	57.5	1.536	0.5	253.10	179.00	117.90	38.40	135.20	140.50
16	54.4	1.149	0.5	200.90	161.67	83.07	36.27	117.80	125.63
17	55.4	0.880	0.5	185.30	167.33	64.97	36.93	120.37	130.57
18	57.0	1.549	0.5	249.97	175.67	117.83	37.93	132.10	137.67
19	57.4	1.280	0.5	230.60	178.33	97.93	38.23	132.63	139.80
20	50.7	1.037	0.5	211.80	143	70.10	33.8	141.70	109.20
Disability	Vehicle Speed (mph)	Reaction Time (s)		Stopping Distance (ft)		Reaction Distance (ft)		Braking Distance (ft)	
No	Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average	Average	Ideal Average
21	57.5	0.776	0.5	221.10	179.00	87.90	38.33	133.20	140.33
22	57.2	1.058	0.5	212.30	177.33	80.80	38.20	131.50	139.17
23	54.8	0.668	0.5	164.27	164.00	48.43	36.50	115.83	127.57
24	52.6	1.990	0.5	257.55	152.50	140.50	35.00	117.10	117.35
25	52.9	1.058	0.5	181.43	154.00	74.53	35.23	106.87	118.57
26	57.5	1.057	0.5	211.43	179.00	81.10	38.37	130.30	140.50
27	57.5	0.823	0.5	188.97	178.67	63.17	38.37	125.77	140.30
28	55.8	1.522	0.5	230.40	169.00	113.10	37.20	117.30	132.00
29	57.5	1.102	0.5	213.50	179.00	84.53	38.40	128.97	140.47
30	53.6	1.214	0.5	227.17	158.00	86.73	35.77	140.43	122.13

Appendix C: (Continued)

C.2. Steering Data for Able Bodied Individuals

Steering data (lane width, vehicle position, vehicle speed, and posted speed limit) was taken for each of the 30 participants at 0.2 second intervals. In all cases, the first data point was taken one time interval before the vehicle began in motion; the last data point was taken as the participant reached the round-about and the posted speed limit is reduced. Lane width and position are relative. The vehicle is inside of the lane when position is less than 2100 and greater than 900. Posted speed limit and posted vehicle speed are in km/hr. A complete record of steering data was too extensive for inclusion in this paper; however, it is on record at the University of South Florida.

Table C.4 - Sample Steering, Data, Group 1, Participant 2

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
0	3000	1901	0	90	3000	1901	0	90	3000	1901	0	90
0.2	3000	1901	1	90	3000	1901	1	90	3000	1901	1	90
0.4	3000	1901	1	90	3000	1901	1	90	3000	1901	4	90
0.6	3000	1901	2	90	3000	1901	1	90	3000	1901	6	90
0.8	3000	1901	3	90	3000	1901	2	90	3000	1901	9	90
1	3000	1901	5	90	3000	1901	3	90	3000	1901	12	90
1.2	3000	1901	6	90	3000	1901	4	90	3000	1902	15	90
1.4	3000	1901	8	90	3000	1901	6	90	3000	1909	17	90
1.6	3000	1901	9	90	3000	1901	8	90	3000	1918	20	90
1.8	3000	1901	11	90	3000	1901	10	90	3000	1929	23	90
2	3000	1901	12	90	3000	1901	12	90	3000	1943	25	90
2.2	3000	1901	14	90	3000	1901	14	90	3000	1959	26	90
2.4	3000	1901	15	90	3000	1901	17	90	3000	1978	27	90
2.6	3000	1901	17	90	3000	1901	19	90	3000	1999	27	90
2.8	3000	1896	19	90	3000	1896	21	90	3000	2031	28	90
3	3000	1892	21	90	3000	1888	24	90	3000	2059	29	90
3.2	3000	1892	22	90	3000	1881	25	90	3000	2076	31	90
3.4	3000	1892	24	90	3000	1871	27	90	3000	2078	32	90
3.6	3000	1892	26	90	3000	1857	28	90	3000	2070	33	90
3.8	3000	1886	27	90	3000	1843	30	90	3000	2049	34	90
4	3000	1878	29	90	3000	1827	32	90	3000	2019	35	90
4.2	3000	1864	31	90	3000	1813	33	90	3000	1984	36	90
4.4	3000	1857	32	90	3000	1800	34	90	3000	1941	37	90
4.6	3000	1850	32	90	3000	1785	34	90	3000	1889	38	90
4.8	3000	1842	33	90	3000	1772	35	90	3000	1825	39	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
5	3000	1835	34	90	3000	1764	35	90	3000	1744	40	90
5.2	3000	1828	35	90	3000	1757	36	90	3000	1676	41	90
5.4	3000	1819	36	90	3000	1750	36	90	3000	1615	42	90
5.6	3000	1807	37	90	3000	1743	37	90	3000	1542	44	90
5.8	3000	1792	38	90	3000	1736	37	90	3000	1497	45	90
6	3000	1772	38	90	3000	1732	37	90	3000	1453	46	90
6.2	3000	1758	39	90	3000	1732	38	90	3000	1424	48	90
6.4	3000	1743	40	90	3000	1732	38	90	3000	1403	49	90
6.6	3000	1728	40	90	3000	1732	38	90	3000	1392	50	90
6.8	3000	1714	41	90	3000	1732	39	90	3000	1390	52	90
7	3000	1700	41	90	3000	1732	39	90	3000	1402	54	90
7.2	3000	1686	41	90	3000	1732	39	90	3000	1431	55	90
7.4	3000	1672	42	90	3000	1732	39	90	3000	1468	57	90
7.6	3000	1661	42	90	3000	1732	40	90	3000	1529	58	90
7.8	3000	1654	43	90	3000	1732	40	90	3000	1606	58	90
8	3000	1647	43	90	3000	1732	40	90	3000	1685	58	90
8.2	3000	1640	43	90	3000	1732	40	90	3000	1774	57	90
8.4	3000	1633	44	90	3000	1732	41	90	3000	1876	57	90
8.6	3000	1624	44	90	3000	1732	41	90	3000	1991	58	90
8.8	3000	1615	44	90	3000	1732	42	90	3000	2136	59	90
9	3000	1608	44	90	3000	1733	42	90	3000	2251	59	90
9.2	3000	1606	45	90	3000	1741	43	90	3000	2346	59	90
9.4	3000	1606	45	90	3000	1748	44	90	3000	2419	59	90
9.6	3000	1606	45	90	3000	1758	44	90	3000	2472	59	90
9.8	3000	1606	45	90	3000	1772	45	90	3000	2505	60	90
10	3000	1606	46	90	3000	1789	44	90	3000	2520	60	90
10.2	3000	1606	46	90	3000	1807	44	90	3000	2513	61	90
10.4	3000	1606	46	90	3000	1828	43	90	3000	2483	61	90
10.6	3000	1612	46	90	3000	1849	43	90	3000	2417	62	90
10.8	3000	1619	46	90	3000	1870	42	90	3000	2335	62	90
11	3000	1626	46	90	3000	1889	41	90	3000	2187	63	90
11.2	3000	1631	46	90	3000	1904	40	90	3000	2046	64	90
11.4	3000	1631	46	90	3000	1920	40	90	3000	1880	64	90
11.6	3000	1631	46	90	3000	1934	39	90	3000	1676	65	90
11.8	3000	1631	47	90	3000	1948	38	90	3000	1506	65	90
12	3000	1631	47	90	3000	1963	38	90	3000	1349	65	90
12.2	3000	1632	47	90	3000	1971	37	90	3000	1192	66	90
12.4	3000	1639	48	90	3000	1978	37	90	3000	1071	67	90
12.6	3000	1645	48	90	3000	1985	37	90	3000	995	67	90
12.8	3000	1653	48	90	3000	1992	37	90	3000	948	68	90
13	3000	1663	48	90	3000	1999	37	90	3000	929	68	90
13.2	3000	1674	48	90	3000	2007	38	90	3000	940	69	90
13.4	3000	1685	48	90	3000	2014	38	90	3000	990	69	90
13.6	3000	1697	49	90	3000	2014	39	90	3000	1066	70	90
13.8	3000	1704	49	90	3000	2014	39	90	3000	1177	70	90
14	3000	1711	49	90	3000	2014	40	90	3000	1284	69	90
14.2	3000	1718	49	90	3000	2014	40	90	3000	1397	69	90
14.4	3000	1725	49	90	3000	2012	41	90	3000	1501	69	90
14.6	3000	1732	49	90	3000	2005	42	90	3000	1588	69	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
14.8	3000	1739	49	90	3000	1997	43	90	3000	1651	69	90
15	3000	1746	50	90	3000	1990	43	90	3000	1687	69	90
15.2	3000	1753	50	90	3000	1981	44	90	3000	1696	70	90
15.4	3000	1760	50	90	3000	1967	44	90	3000	1679	70	90
15.6	3000	1766	50	90	3000	1953	45	90	3000	1635	70	90
15.8	3000	1766	50	90	3000	1938	45	90	3000	1565	69	90
16	3000	1766	50	90	3000	1919	45	90	3000	1466	70	90
16.2	3000	1766	50	90	3000	1899	45	90	3000	1341	70	90
16.4	3000	1766	50	90	3000	1878	46	90	3000	1187	71	90
16.6	3000	1766	50	90	3000	1854	46	90	3000	941	71	90
16.8	3000	1766	51	90	3000	1833	46	90	3000	732	71	90
17	3000	1766	51	90	3000	1812	46	90	3000	525	71	90
17.2	3000	1766	51	90	3000	1788	47	90	3000	341	71	90
17.4	3000	1766	51	90	3000	1773	47	90	3000	164	71	90
17.6	3000	1763	51	90	3000	1759	48	90	3000	43	71	90
17.8	3000	1757	51	90	3000	1749	48	90	3000	-62	71	90
18	3000	1757	51	90	3000	1742	48	90	3000	-124	71	90
18.2	3000	1757	51	90	3000	1738	49	90	3000	-159	71	90
18.4	3000	1757	51	90	3000	1738	49	90	3000	-159	71	90
18.6	3000	1757	51	90	3000	1740	49	90	3000	-124	71	90
18.8	3000	1757	51	90	3000	1747	49	90	3000	-63	72	90
19	3000	1757	51	90	3000	1754	49	90	3000	27	72	90
19.2	3000	1757	51	90	3000	1765	50	90	3000	146	71	90
19.4	3000	1757	51	90	3000	1779	50	90	3000	293	71	90
19.6	3000	1753	51	90	3000	1793	50	90	3000	467	70	90
19.8	3000	1745	51	90	3000	1812	50	90	3000	664	70	90
20	3000	1731	50	90	3000	1825	51	90	3000	869	69	90
20.2	3000	1717	50	90	3000	1839	51	90	3000	1115	68	90
20.4	3000	1703	50	90	3000	1853	51	90	3000	1239	68	90
20.6	3000	1691	50	90	3000	1866	51	90	3000	1312	67	90
20.8	3000	1684	50	90	3000	1883	52	90	3000	1343	67	90
21	3000	1677	50	90	3000	1896	52	90	3000	1364	66	90
21.2	3000	1669	50	90	3000	1905	52	90	3000	1379	66	90
21.4	3000	1661	50	90	3000	1911	52	90	3000	1395	65	90
21.6	3000	1654	50	90	3000	1918	53	90	3000	1409	65	90
21.8	3000	1646	49	90	3000	1918	53	90	3000	1423	64	90
22	3000	1639	49	90	3000	1914	53	90	3000	1438	64	90
22.2	3000	1632	49	90	3000	1903	53	90	3000	1452	63	90
22.4	3000	1624	49	90	3000	1888	54	90	3000	1466	63	90
22.6	3000	1616	49	90	3000	1867	54	90	3000	1482	63	90
22.8	3000	1609	49	90	3000	1839	54	90	3000	1498	62	90
23	3000	1602	49	90	3000	1804	54	90	3000	1513	62	90
23.2	3000	1595	49	90	3000	1757	55	90	3000	1526	61	90
23.4	3000	1593	49	90	3000	1714	55	90	3000	1541	61	90
23.6	3000	1594	49	90	3000	1668	55	90	3000	1555	60	60
23.8	3000	1601	48	90	3000	1615	55	90	3000	1568	60	60
24	3000	1608	48	90	3000	1573	55	90	3000	1583	60	60
24.2	3000	1616	48	90	3000	1514	55	90	3000	1599	59	60
24.4	3000	1619	48	90	3000	1463	55	90	3000	1617	59	60

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
24.6	3000	1619	48	90	3000	1420	56	90	3000	1631	59	60
24.8	3000	1623	48	90	3000	1379	56	90	3000	1645	58	60
25	3000	1630	48	90	3000	1342	56	90	3000	1661	58	60
25.2	3000	1642	48	90	3000	1307	56	90	3000	1676	57	60
25.4	3000	1656	48	90	3000	1274	56	90	3000	1689	56	60
25.6	3000	1670	48	90	3000	1245	56	90	3000	1703	56	60
25.8	3000	1684	48	90	3000	1217	56	90	3000	1716	55	60
26	3000	1698	48	90	3000	1191	56	90	3000	1733	54	60
26.2	3000	1712	48	90	3000	1170	56	90	3000	1745	53	60
26.4	3000	1726	47	90	3000	1149	56	90	3000	1755	52	60
26.6	3000	1740	47	90	3000	1131	56	90	3000	1761	52	60
26.8	3000	1756	47	90	3000	1118	55	90	3000	1763	51	60
27	3000	1770	47	90	3000	1110	55	90	3000	1763	51	60
27.2	3000	1786	47	90	3000	1110	54	90	3000	1757	51	60
27.4	3000	1800	47	90	3000	1117	54	90	3000	1746	51	60
27.6	3000	1814	47	90	3000	1132	53	90	3000	1729	50	60
27.8	3000	1828	47	90	3000	1153	53	90	3000	1708	50	60
28	3000	1842	47	90	3000	1188	53	90	3000	1680	49	60
28.2	3000	1857	47	90	3000	1226	52	90	3000	1652	49	60
28.4	3000	1870	47	90	3000	1270	52	90	3000	1620	49	60
28.6	3000	1884	47	90	3000	1320	52	90	3000	1585	49	60
28.8	3000	1895	47	90	3000	1372	52	90	3000	1545	49	60
29	3000	1902	47	90	3000	1430	52	90	3000	1501	49	60
29.2	3000	1906	47	90	3000	1488	52	90	3000	1453	48	60
29.4	3000	1906	47	90	3000	1551	51	90	3000	1394	48	60
29.6	3000	1903	47	90	3000	1613	51	90	3000	1339	47	60
29.8	3000	1895	47	90	3000	1674	51	90	3000	1285	47	60
30	3000	1882	47	90	3000	1733	51	90	3000	1228	46	60
30.2	3000	1866	47	90	3000	1789	51	90	3000	1172	46	60
30.4	3000	1849	46	90	3000	1849	51	90	3000	1119	45	60
30.6	3000	1832	46	90	3000	1894	51	90	3000	1071	45	60
30.8	3000	1816	46	90	3000	1931	51	90	3000	1027	44	60
31	3000	1799	46	90	3000	1961	51	90	3000	988	44	60
31.2	3000	1781	46	90	3000	1986	51	60	3000	952	44	60
31.4	3000	1764	46	90	3000	2000	51	60	3000	927	44	60
31.6	3000	1747	46	60	3000	2008	51	60	3000	910	44	60
31.8	3000	1731	46	60	3000	2010	51	60	3000	901	45	60
32	3000	1712	46	60	3000	2005	51	60	3000	900	45	60
32.2	3000	1694	46	60	3000	1991	51	60	3000	907	46	60
32.4	3000	1675	46	60	3000	1972	51	60	3000	924	46	60
32.6	3000	1654	46	60	3000	1945	51	60	3000	948	47	60
32.8	3000	1635	46	60	3000	1912	51	60	3000	988	47	60
33	3000	1614	46	60	3000	1872	51	60	3000	1039	47	60
33.2	3000	1600	46	60	3000	1825	51	60	3000	1092	47	60
33.4	3000	1587	46	60	3000	1773	51	60	3000	1154	46	60
33.6	3000	1571	46	60	3000	1705	51	60	3000	1223	46	60
33.8	3000	1557	46	60	3000	1636	51	60	3000	1300	45	60
34	3000	1543	45	60	3000	1576	51	60	3000	1382	45	60
34.2	3000	1528	45	60	3000	1522	51	60	3000	1469	44	60

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
34.4	3000	1512	45	60	3000	1474	51	60	3000	1558	43	60
34.6	3000	1498	44	60	3000	1429	52	60	3000	1659	42	60
34.8	3000	1491	44	60	3000	1400	52	60	3000	1747	41	60
35	3000	1488	43	60	3000	1382	52	60	3000	1839	41	30
35.2	3000	1480	43	60	3000	1373	53	60	3000	1887	40	30
35.4	3000	1498	43	60	3000	1375	53	60	3000	1910	40	30
35.6	3000	1510	43	60	3000	1386	53	60	3000	1922	39	30
35.8	3000	1524	43	60	3000	1408	53	60	3000	1929	39	30
36	3000	1538	42	60	3000	1438	53	60	3000	1937	38	30
36.2	3000	1550	42	60	3000	1475	53	60	3000	1942	36	30
36.4	3000	1557	42	60	3000	1517	53	60	3000	1942	35	30
36.6	3000	1559	42	60	3000	1566	53	60	3000	1942	34	30
36.8	3000	1560	42	60	3000	1607	53	60	3000	1942	33	30
37	3000	1567	42	60	3000	1648	52	60	3000	1938	32	30
37.2	3000	1573	42	60	3000	1689	52	60	3000	1931	32	30
37.4	3000	1583	42	60	3000	1730	52	60	3000	1924	31	30
37.6	3000	1593	43	60	3000	1769	52	60	3000	1916	30	30
37.8	3000	1599	43	60	3000	1803	52	60	3000	1908	29	30
38	3000	1607	43	60	3000	1837	51	60	3000	1895	28	30
38.2	3000	1614	43	60	3000	1868	51	60	3000	1881	28	30
38.4	3000	1620	43	60	3000	1892	51	60	3000	1867	27	30
38.6	3000	1628	43	60	3000	1908	51	60	3000	1853	27	30
38.8	3000	1635	43	60	3000	1920	51	60	3000	1834	26	30
39	3000	1642	43	60	3000	1927	51	60	3000	1816	26	30
39.2	3000	1649	43	60	3000	1927	51	60	3000	1795	25	30
39.4	3000	1656	43	60	3000	1922	51	60	3000	1771	25	30
39.6	3000	1663	44	60	3000	1915	51	60	3000	1751	25	30
39.8	3000	1671	44	60	3000	1904	51	60	3000	1738	24	30
40	3000	1678	44	60	3000	1890	50	60	3000	1569	24	30
40.2	3000	1685	44	60	3000	1872	50	60	3000	1471	23	30
40.4	3000	1691	44	60	3000	1851	50	60	3000	1423	23	30
40.6	3000	1698	44	60	3000	1835	49	60	3000	1411	23	30
40.8	3000	1699	44	60	3000	1821	49	60	3000	1192	22	30
41	3000	1699	44	60	3000	1812	48	60	3000	1090	22	30
41.2	3000	1699	44	60	3000	1808	48	60	3000	1110	22	30
41.4	3000	1699	44	60	3000	1808	48	60	3000	1231	21	30
41.6	3000	1699	44	60	3000	1814	47	60	3000	1227	21	30
41.8	3000	1693	44	60	3000	1821	47	60	3000	1251	21	30
42	3000	1686	44	60	3000	1828	46	60	3000	1368	21	30
42.2	3000	1679	43	60	3000	1835	45	60	3000	1600	21	30
42.4	3000	1672	43	60	3000	1842	45	30	3000	1804	22	30
42.6	3000	1666	43	60	3000	1850	44	30	3000	1852	24	30
42.8	3000	1657	43	60	3000	1859	44	30	3000	1977	26	30
43	3000	1647	43	60	3000	1866	43	30	3000	1920	28	30
43.2	3000	1634	42	60	3000	1873	43	30	3000	1892	28	30
43.4	3000	1620	42	60	3000	1873	42	30	3000	1761	28	30
43.6	3000	1606	42	60	3000	1873	41	30	3000	1564	28	30
43.8	3000	1593	41	60	3000	1873	41	30	3000	1510	27	30
44	3000	1580	41	60	3000	1868	40	30	3000	1409	26	30

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
44.2	3000	1568	41	60	3000	1860	40	30	3000	1479	26	30
44.4	3000	1555	41	60	3000	1853	39	30	3000	1547	25	30
44.6	3000	1541	41	60	3000	1845	38	30	2500	1388	25	30
44.8	3000	1527	40	30	3000	1831	35	30	2500	1346	25	30
45	3000	1511	40	30	3000	1817	32	30	3000	1611	26	30
45.2	3000	1497	40	30	3000	1802	28	30	3000	1583	26	30
45.4	3000	1483	39	30	3000	1794	26	30	3000	1411	26	30
45.6	3000	1465	39	30	3000	1790	24	30	3000	1351	25	30
45.8	3000	1456	39	30	3000	1790	24	30	3000	1443	25	30
46	3000	1449	39	30	3000	1793	23	30	3000	1438	24	30
46.2	3000	1438	39	30	3000	1800	23	30	3000	1520	24	30
46.4	3000	1422	38	30	3000	1814	22	30	3000	1744	23	30
46.6	3000	1408	38	30	3000	1791	22	30	3000	1888	24	30
46.8	3000	1392	37	30	3000	1658	23	30	3000	2068	25	30
47	3000	1378	36	30	3000	1526	23	30	3000	2169	26	30
47.2	3000	1364	35	30	3000	1426	25	30	3000	2325	28	30
47.4	3000	1350	34	30	3000	1147	27	30	3000	2425	30	30
47.6	3000	1338	33	30	3000	784	28	30	3000	2272	31	30
47.8	3000	1331	33	30	3000	483	30	30	3000	1852	32	30
48	3000	1324	32	30	3000	134	31	30	3000	1491	32	30
48.2	3000	1323	31	30	3000	-453	32	30	3000	1232	31	30
48.4	3000	1330	30	30	3000	-797	32	30	3000	773	30	30
48.6	3000	1364	30	30	3000	-962	31	30	3000	397	30	90
48.8	3000	1410	29	30	3000	-1342	31	30	3000	216	30	90
49	3000	1358	28	30	3000	-1526	30	30	3000	204	30	90
49.2	3000	1301	28	30	3000	-1616	29	30	3000	354	30	90
49.4	3000	1306	27	30	3000	-1698	29	30	3000	633	31	90
49.6	3000	1302	27	30	3000	-1572	28	30	3000	944	31	90
49.8	3000	1093	26	30	3000	-1526	27	30	3000	1351	31	90
50	3000	1017	26	30	3000	-1406	27	30	3000	1707	32	90
50.2	3000	1093	25	30	3000	-1137	26	30	3000	2045	32	90
50.4	3000	1048	25	30	3000	-919	26	30	3000	2416	31	90
50.6	3000	997	25	30	3000	-628	25	30	3000	2598	31	90
50.8	3000	1064	24	30	3000	-268	25	30	3000	2657	31	90
51	3000	1268	24	30	3000	83	25	30	3000	2560	31	90
51.2	3000	1284	23	30	2500	185	24	30	3000	2267	31	90
51.4	3000	1315	23	30	2500	535	24	30	3000	1830	30	90
51.6	3000	1408	23	30	3000	1173	24	30	3000	1305	30	90
51.8	3000	1404	22	30	3000	1571	25	30	3000	824	30	90
52	3000	1443	22	30	3000	1824	26	30	3000	336	30	90
52.2	3000	1563	22	30	3000	2113	26	30	3000	-134	30	90
52.4	3000	1550	22	30	3000	2471	27	30	3000	-593	29	90
52.6	3000	1542	22	30	3000	2653	27	30	3000	-1039	29	90
52.8	3000	1623	22	30	3000	2781	28	30	3000	-1446	29	90
53	3000	1648	23	30	3000	2889	29	30	3000	-1789	29	90
53.2	3000	1665	23	30	3000	2901	30	30	3000	-2072	29	90
53.4	3000	1735	23	30	3000	2755	30	30	3000	-2327	29	90
53.6	3000	1753	23	30	3000	2697	31	30	3000	-2573	29	90
53.8	2500	1513	23	30	3000	2540	32	30	3000	-2816	28	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
54	2500	1428	23	30	3000	2274	32	30	3000	-3053	28	90
54.2	3000	1658	23	30	3000	1868	32	30	3000	-3222	28	90
54.4	3000	1699	23	30	3000	1726	31	30	3000	-3325	28	90
54.6	3000	1543	23	30	3000	1665	31	30	3000	-3293	28	90
54.8	3000	1476	23	30	3000	1592	30	30	3000	-3191	28	90
55	3000	1505	23	30	3000	1579	30	90	3000	-3048	28	90
55.2	3000	1631	23	30	3000	1684	30	90	3000	-2869	28	90
55.4	3000	1556	23	30	3000	1860	30	90	3000	-2709	27	90
55.6	3000	1566	23	30	3000	2100	30	90	3000	-2553	27	90
55.8	3000	1621	23	30	3000	2446	30	90	3000	-2371	27	90
56	3000	1574	23	30	3000	2775	30	90	3000	-2216	27	90
56.2	3000	1528	23	30	3000	3103	30	90	3000	-2034	29	90
56.4	3000	1441	23	30	3000	3442	30	90	3000	-1815	30	90
56.6	3000	1432	23	30	3000	3653	30	90	3000	-1616	31	90
56.8	3000	1501	23	30	3000	3772	30	90	3000	-1438	33	90
57	3000	1451	23	30	3000	3801	30	90	3000	-1253	34	90
57.2	3000	1456	23	30	3000	3734	30	90	3000	-1061	36	90
57.4	3000	1303	23	30	3000	3672	0	90	3000	-833	37	90
57.6	3000	1236	23	30	3000	3672	0	90	3000	-637	36	90
57.8	3000	1241	23	30	3000	3672	0	90	3000	-444	36	90
58	3000	1319	22	30	3000	3672	0	90	3000	-263	36	90
58.2	3000	1310	22	30	3000	3672	0	90	3000	-93	36	90
58.4	3000	1286	22	30	3000	3672	0	90	3000	67	36	90
58.6	3000	1271	23	90	3000	3672	0	90	3000	221	37	90
58.8	3000	1227	23	90	3000	3672	0	90	3000	392	38	90
59	3000	1196	23	90	3000	3672	0	90	3000	552	40	90
59.2	3000	1181	24	90	3000	3672	0	90	3000	679	40	90
59.4	3000	1186	25	90	3000	3672	0	90	3000	792	41	90
59.6	3000	1207	26	90	3000	3672	0	90	3000	892	42	90
59.8	3000	1240	26	90	3000	3672	0	90	3000	979	43	90
60	3000	1284	27	90	3000	3672	0	90	3000	1052	45	90
60.2	3000	1335	28	90	3000	3672	0	90	3000	1110	46	90
60.4	3000	1395	29	90	3000	3672	0	90	3000	1151	48	90
60.6	3000	1461	29	90	3000	3672	0	90	3000	1176	49	90
60.8	3000	1542	30	90	3000	3672	0	90	3000	1192	50	90
61	3000	1614	31	90	3000	3672	0	90	3000	1187	51	90
61.2	3000	1685	31	90	3000	3672	0	90	3000	1160	51	90
61.4	3000	1747	32	90	3000	3672	0	90	3000	1176	53	90
61.6	3000	1804	32	90	3000	3672	0	90	3000	1214	53	90
61.8	3000	1857	32	90	3000	3672	0	90	3000	1282	54	90
62	3000	1907	32	90	3000	3672	0	90	3000	1362	54	90
62.2	3000	1947	33	90	3000	3672	0	90	3000	1479	54	90
62.4	3000	1975	33	90	3000	3672	0	90	3000	1604	55	90
62.6	3000	1993	34	90	3000	3672	0	90	3000	1719	55	90
62.8	3000	1997	34	90	3000	3672	0	90	3000	1756	56	90
63	3000	1991	34	90	3000	3672	0	90	3000	1731	56	90
63.2	3000	1979	35	90	3000	3672	0	90	3000	1669	56	90
63.4	3000	1960	35	90	3000	3672	0	90	3000	1592	56	90
63.6	3000	1938	35	90	3000	3672	0	90	3000	1513	55	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
63.8	3000	1916	36	90	3000	3672	0	90	3000	1439	55	90
64	3000	1893	36	90	3000	3672	0	90	3000	1359	54	90
64.2	3000	1874	36	90	3000	3672	0	90	3000	1293	54	90
64.4	3000	1855	36	90	3000	3672	0	90	3000	1231	55	90
64.6	3000	1836	36	90	3000	3672	0	90	3000	1172	56	90
64.8	3000	1817	35	90	3000	3672	0	90	3000	1109	57	90
65	3000	1793	35	90	3000	3672	0	90	3000	1060	58	90
65.2	3000	1767	35	90	3000	3672	0	90	3000	1015	59	90
65.4	3000	1740	35	90	3000	3672	0	90	3000	972	60	90
65.6	3000	1712	34	90	3000	3672	0	90	3000	927	61	90
65.8	3000	1690	34	90	3000	3672	0	90	3000	893	62	90
66	3000	1672	34	90	3000	3672	0	90	3000	860	63	90
66.2	3000	1656	34	90	3000	3672	0	90	3000	834	63	90
66.4	3000	1639	34	90	3000	3672	0	90	3000	813	64	90
66.6	3000	1622	34	90	3000	3672	0	90	3000	798	65	90
66.8	3000	1605	34	90	3000	3672	0	90	3000	785	66	90
67	3000	1593	34	90	3000	3672	0	90	3000	778	67	90
67.2	3000	1584	34	90	3000	3672	0	90	3000	778	68	90
67.4	3000	1581	34	90	3000	3672	0	90	3000	782	68	90
67.6	3000	1579	34	90	3000	3672	0	90	3000	790	69	90
67.8	3000	1575	34	90	3000	3672	0	90	3000	806	70	90
68	3000	1573	34	90	3000	3672	0	90	3000	826	71	90
68.2	3000	1565	34	90	3000	3672	0	90	3000	853	72	90
68.4	3000	1555	34	90	3000	3672	0	90	3000	892	73	90
68.6	3000	1546	35	90	3000	3672	0	90	3000	932	74	90
68.8	3000	1536	35	90	3000	3672	0	90	3000	979	75	90
69	3000	1527	35	90	3000	3672	0	90	3000	1033	76	90
69.2	3000	1512	35	90	3000	3672	0	90	3000	1093	76	90
69.4	3000	1496	36	90	3000	3672	0	90	3000	1156	77	90
69.6	3000	1474	36	90	3000	3672	0	90	3000	1217	78	90
69.8	3000	1465	36	90	3000	3672	0	90	3000	1274	79	90
70	3000	1459	36	90	3000	3672	0	90	3000	1327	80	90
70.2	3000	1457	36	90	3000	3672	0	90	3000	1375	80	90
70.4	3000	1461	36	90	3000	3672	0	90	3000	1417	81	90
70.6	3000	1468	36	90	3000	3672	0	90	3000	1452	82	90
70.8	3000	1479	36	90	3000	3672	0	90	3000	1478	83	90
71	3000	1490	36	90	3000	3672	0	90	3000	1495	83	90
71.2	3000	1496	36	90	3000	3672	0	90	3000	1506	84	90
71.4	3000	1479	36	90	3000	3672	0	90	3000	1510	85	90
71.6	3000	1441	37	90	3000	3672	0	90	3000	1505	85	90
71.8	3000	1412	37	90	3000	3672	0	90	3000	1493	86	90
72	3000	1407	37	90	3000	3672	0	90	3000	1466	86	90
72.2	3000	1403	37	90	3000	3672	0	90	3000	1434	87	90
72.4	3000	1399	37	90	3000	3672	0	90	3000	1394	87	90
72.6	3000	1389	37	90	3000	3672	0	90	3000	1340	87	90
72.8	3000	1378	36	90	3000	3672	0	90	3000	1285	87	90
73	3000	1380	36	90	3000	3672	0	90	3000	1221	87	90
73.2	3000	1387	36	90	3000	3672	0	90	3000	1151	86	90
73.4	3000	1393	36	90	3000	3672	0	90	3000	1079	86	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
73.6	3000	1393	36	90	3000	3672	0	90	3000	1005	85	90
73.8	3000	1393	36	90	3000	3672	0	90	3000	924	85	90
74	3000	1393	36	90	3000	3672	0	90	3000	836	84	90
74.2	3000	1393	35	90	3000	3672	0	90	3000	742	84	90
74.4	3000	1393	35	90	3000	3672	0	90	3000	640	83	90
74.6	3000	1393	35	90	3000	3672	0	90	3000	524	83	90
74.8	3000	1393	35	90	3000	3672	0	90	3000	445	82	90
75	3000	1393	35	90	3000	3672	0	90	3000	400	82	90
75.2	3000	1393	35	90	3000	3672	0	90	3000	395	81	90
75.4	3000	1400	35	90	3000	3672	0	90	3000	433	81	90
75.6	3000	1408	36	90	3000	3672	0	90	3000	531	81	90
75.8	3000	1415	36	90	3000	3672	0	90	3000	688	82	90
76	3000	1422	36	90	3000	3672	0	90	3000	870	82	90
76.2	3000	1431	37	90	3000	3672	0	90	3000	1096	82	90
76.4	3000	1445	37	90	3000	3672	0	90	3000	1402	83	90
76.6	3000	1459	37	90	3000	3672	0	90	3000	1690	83	90
76.8	3000	1471	38	90	3000	3672	0	90	3000	1975	83	90
77	3000	1478	38	90	3000	3672	0	90	3000	2232	83	90
77.2	3000	1485	39	90	3000	3672	0	90	3000	2453	84	90
77.4	3000	1492	39	90	3000	3672	0	90	3000	2671	84	90
77.6	3000	1504	40	90	3000	3672	0	90	3000	2798	84	90
77.8	3000	1519	40	90	3000	3672	0	90	3000	2909	84	90
78	3000	1538	41	90	3000	3672	0	90	3000	3005	84	90
78.2	3000	1555	42	90	3000	3672	0	90	3000	3080	84	90
78.4	3000	1569	42	90	3000	3672	0	90	3000	3098	84	90
78.6	3000	1583	43	90	3000	3672	0	90	3000	3085	84	90
78.8	3000	1597	43	90	3000	3672	0	90	3000	3038	85	90
79	3000	1611	44	90	3000	3672	0	90	3000	2975	85	90
79.2	3000	1625	44	90	3000	3672	0	90	3000	2896	85	90
79.4	3000	1641	45	90	3000	3672	0	90	3000	2794	85	90
79.6	3000	1655	46	90	3000	3672	0	90	3000	2647	85	90
79.8	3000	1665	46	90	3000	3672	0	90	3000	2471	85	90
80	3000	1674	47	90	3000	3672	0	90	3000	2299	85	90
80.2	3000	1682	47	90	3000	3672	0	90	3000	2112	84	90
80.4	3000	1688	48	90	3000	3672	0	90	3000	1895	84	90
80.6	3000	1693	49	90	3000	3672	0	90	3000	1718	84	90
80.8	3000	1693	49	90	3000	3672	0	90	3000	1551	84	90
81	3000	1693	50	90	3000	3672	0	90	3000	1395	84	90
81.2	3000	1693	50	90	3000	3672	0	90	3000	1251	84	90
81.4	3000	1688	51	90	3000	3672	0	90	3000	1117	84	90
81.6	3000	1681	51	90	3000	3672	0	90	3000	976	84	90
81.8	3000	1669	51	90	3000	3672	0	90	3000	867	84	90
82	3000	1655	51	90	3000	3672	0	90	3000	770	84	90
82.2	3000	1639	52	90	3000	3672	0	90	3000	684	84	90
82.4	3000	1620	52	90	3000	3672	0	90	3000	608	84	90
82.6	3000	1605	53	90	3000	3672	1	90	3000	545	84	90
82.8	3000	1591	53	90	3000	3682	3	90	3000	486	85	90
83	3000	1578	53	90	3000	3700	5	90	3000	445	85	90
83.2	3000	1561	54	90	3000	3724	7	90	3000	417	85	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
83.4	3000	1540	54	90	3000	3743	9	90	3000	399	86	90
83.6	3000	1519	55	90	3000	3747	11	90	3000	395	86	90
83.8	3000	1494	55	90	3000	3732	11	90	3000	404	86	90
84	3000	1466	56	90	3000	3701	10	90	3000	423	87	90
84.2	3000	1440	56	90	3000	3657	10	90	3000	455	87	90
84.4	3000	1416	57	90	3000	3607	9	90	3000	500	88	90
84.6	3000	1401	57	90	3000	3548	9	90	3000	557	88	90
84.8	3000	1387	58	90	3000	3485	9	90	3000	627	88	90
85	3000	1372	58	90	3000	3414	8	90	3000	739	89	90
85.2	3000	1352	59	90	3000	3331	8	90	3000	839	89	90
85.4	3000	1334	59	90	3000	3257	8	90	3000	953	90	90
85.6	3000	1323	59	90	3000	3185	7	90	3000	1080	90	90
85.8	3000	1320	60	90	3000	3112	7	90	3000	1221	91	90
86	3000	1326	60	90	3000	3038	7	90	3000	1368	91	90
86.2	3000	1343	61	90	3000	2966	6	90	3000	1511	92	90
86.4	3000	1366	61	90	3000	2892	6	90	3000	1653	92	90
86.6	3000	1391	62	90	3000	2820	6	90	3000	1748	93	90
86.8	3000	1414	62	90	3000	2749	6	90	3000	1814	93	90
87	3000	1435	63	90	3000	2679	5	90	3000	1849	93	90
87.2	3000	1458	63	90	3000	2620	5	90	3000	1852	94	90
87.4	3000	1472	64	90	3000	2571	5	90	3000	1822	94	90
87.6	3000	1486	64	90	3000	2523	4	90	3000	1759	95	90
87.8	3000	1499	65	90	3000	2483	4	90	3000	1645	95	90
88	3000	1507	65	90	3000	2448	4	90	3000	1518	95	90
88.2	3000	1514	66	90	3000	2421	4	90	3000	1391	96	90
88.4	3000	1520	66	90	3000	2397	4	90	3000	1280	96	90
88.6	3000	1520	67	90	3000	2376	3	90	3000	1177	97	90
88.8	3000	1519	67	90	3000	2362	3	90	3000	1114	97	90
89	3000	1512	68	90	3000	2350	2	90	3000	1072	98	90
89.2	3000	1510	68	90	3000	2350	0	90	3000	1050	98	90
89.4	3000	1505	69	90	3000	2350	0	90	3000	1051	98	90
89.6	3000	1494	69	90	3000	2350	0	90	3000	1075	99	90
89.8	3000	1480	70	90	3000	2350	0	90	3000	1119	99	90
90	3000	1465	70	90	3000	2350	0	90	3000	1184	100	90
90.2	3000	1447	71	90	3000	2350	0	90	3000	1272	100	90
90.4	3000	1435	71	90	3000	2350	0	90	3000	1383	100	90
90.6	3000	1427	72	90	3000	2350	0	90	3000	1495	100	90
90.8	3000	1431	72	90	3000	2350	0	90	3000	1565	100	90
91	3000	1447	72	90	3000	2350	0	90	3000	1642	99	90
91.2	3000	1473	73	90	3000	2350	0	90	3000	1680	98	90
91.4	3000	1501	73	90	3000	2350	0	90	3000	1683	98	90
91.6	3000	1531	74	90	3000	2350	0	90	3000	1647	98	90
91.8	3000	1560	74	90	3000	2350	0	90	3000	1575	98	90
92	3000	1591	75	90	3000	2350	0	90	3000	1469	97	90
92.2	3000	1620	75	90	3000	2350	0	90	3000	1330	96	90
92.4	3000	1650	75	90	3000	2350	0	90	3000	1129	96	90
92.6	3000	1680	76	90	3000	2350	0	90	3000	931	95	90
92.8	3000	1709	76	90	3000	2350	1	90	3000	721	94	90
93	3000	1733	77	90	3000	2350	2	90	3000	510	94	90

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
93.2	3000	1760	77	90	3000	2350	2	90	3000	310	93	90
93.4	3000	1791	78	90	3000	2350	3	90	3000	148	93	90
93.6	3000	1815	78	90	3000	2350	4	90	3000	21	92	90
93.8	3000	1813	78	90	3000	2350	5	90	3000	-40	92	90
94	3000	1799	78	90	3000	2350	7	90	3000	-64	92	90
94.2	3000	1785	78	90	3000	2350	10	90	3000	-55	92	90
94.4	3000	1771	79	90	3000	2350	13	90	3000	-1	92	90
94.6	3000	1751	79	90	3000	2340	15	90	3000	80	92	90
94.8	3000	1730	79	90	3000	2321	19	90	3000	191	92	90
95	3000	1713	79	90	3000	2284	22	90	3000	318	91	90
95.2	3000	1690	79	90	3000	2237	25	90	3000	469	91	90
95.4	3000	1677	79	90	3000	2201	26	90	3000	592	92	90
95.6	3000	1661	79	90	3000	2165	28	90	3000	700	92	90
95.8	3000	1638	80	90	3000	2127	29	90	3000	794	92	90
96	3000	1610	80	90	3000	2088	30	90	3000	870	92	90
96.2	3000	1577	80	90	3000	2044	30	90	3000	917	92	90
96.4	3000	1541	80	90	3000	1985	32	90	3000	944	93	90
96.6	3000	1504	80	90	3000	1929	33	90	3000	954	93	90
96.8	3000	1465	80	90	3000	1862	34	90	3000	950	93	90
97	3000	1417	80	90	3000	1804	35	90	3000	930	93	90
97.2	3000	1378	81	90	3000	1765	36	90	3000	892	92	90
97.4	3000	1340	81	90	3000	1735	37	90	3000	840	92	90
97.6	3000	1300	81	90	3000	1714	37	90	3000	775	92	90
97.8	3000	1274	81	90	3000	1698	37	90	3000	704	91	90
98	3000	1258	81	90	3000	1684	36	90	3000	671	91	90
98.2	3000	1257	82	90	3000	1677	36	90	3000	686	91	90
98.4	3000	1269	82	90	3000	1670	36	90	3000	751	91	90
98.6	3000	1296	82	90	3000	1675	36	90	3000	866	91	90
98.8	3000	1328	82	90	3000	1675	35	90	3000	1055	91	90
99	3000	1355	82	90	3000	1672	35	90	3000	1234	91	90
99.2	3000	1382	82	90	3000	1667	35	90	3000	1399	90	90
99.4	3000	1407	83	90	3000	1658	35	90	3000	1541	90	90
99.6	3000	1434	83	90	3000	1646	36	90	3000	1658	89	90
99.8	3000	1464	83	90	3000	1626	37	90	3000	1751	89	90
100	3000	1498	83	90	3000	1608	37	90	3000	1820	88	90
100.2	3000	1538	83	90	3000	1584	38	90	3000	1865	87	90
100.4	3000	1579	83	90	3000	1564	39	90	3000	1885	87	90
100.6	3000	1617	84	90	3000	1549	40	90	3000	1884	86	90
100.8	3000	1650	84	90	3000	1540	41	90	3000	1859	86	90
101	3000	1678	84	90	3000	1538	42	90	3000	1814	82	90
101.2	3000	1702	84	90	3000	1536	43	90				
101.4	3000	1720	84	90	3000	1535	44	90				
101.6	3000	1733	84	90	3000	1533	45	90				
101.8	3000	1741	85	90	3000	1527	46	90				
102	3000	1743	85	90	3000	1519	47	90				
102.2	3000	1739	85	90	3000	1504	48	90				
102.4	3000	1729	85	90	3000	1483	49	90				
102.6	3000	1714	85	90	3000	1461	51	90				
102.8	3000	1692	85	90	3000	1435	52	90				

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
103	3000	1659	85	90	3000	1406	53	90				
103.2	3000	1627	85	90	3000	1388	53	90				
103.4	3000	1588	85	90	3000	1378	54	90				
103.6	3000	1546	86	90	3000	1378	54	90				
103.8	3000	1499	86	90	3000	1387	55	90				
104	3000	1468	86	90	3000	1406	55	90				
104.2	3000	1447	86	90	3000	1399	56	90				
104.4	3000	1438	86	90	3000	1359	56	90				
104.6	3000	1436	86	90	3000	1348	56	90				
104.8	3000	1437	86	90	3000	1336	56	90				
105	3000	1437	86	90	3000	1321	57	90				
105.2	3000	1439	87	90	3000	1316	57	90				
105.4	3000	1442	87	90	3000	1323	57	90				
105.6	3000	1446	87	90	3000	1326	58	90				
105.8	3000	1453	87	90	3000	1326	58	90				
106	3000	1460	87	90	3000	1326	58	90				
106.2	3000	1474	87	90	3000	1326	59	90				
106.4	3000	1488	87	90	3000	1333	59	90				
106.6	3000	1502	87	90	3000	1347	60	90				
106.8	3000	1515	87	90	3000	1369	60	90				
107	3000	1523	87	90	3000	1398	61	90				
107.2	3000	1527	88	90	3000	1436	61	90				
107.4	3000	1527	88	90	3000	1489	62	90				
107.6	3000	1527	88	90	3000	1545	62	90				
107.8	3000	1533	88	90	3000	1594	63	90				
108	3000	1480	88	90	3000	1638	63	90				
108.2	3000	1440	88	90	3000	1675	64	90				
108.4	3000	1407	88	90	3000	1707	64	90				
108.6	3000	1376	88	90	3000	1725	65	90				
108.8	3000	1339	88	90	3000	1736	65	90				
109	3000	1305	89	90	3000	1737	66	90				
109.2	3000	1263	89	90	3000	1731	66	90				
109.4	3000	1234	89	90	3000	1723	67	90				
109.6	3000	1215	89	90	3000	1722	67	90				
109.8	3000	1210	89	90	3000	1722	68	90				
110	3000	1217	89	90	3000	1729	68	90				
110.2	3000	1229	89	90	3000	1736	69	90				
110.4	3000	1245	89	90	3000	1741	70	90				
110.6	3000	1266	90	90	3000	1739	70	90				
110.8	3000	1284	90	90	3000	1725	71	90				
111	3000	1302	90	90	3000	1696	71	90				
111.2	3000	1320	90	90	3000	1659	72	90				
111.4	3000	1338	90	90	3000	1613	73	90				
111.6	3000	1356	90	90	3000	1562	73	90				
111.8	3000	1374	90	90	3000	1510	74	90				
112	3000	1392	90	90	3000	1451	74	90				
112.2	3000	1411	90	90	3000	1403	75	90				
112.4	3000	1423	90	90	3000	1364	76	90				
112.6	3000	1429	90	90	3000	1330	76	90				

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
112.8	3000	1433	90	90	3000	1308	77	90				
113	3000	1439	90	90	3000	1293	78	90				
113.2	3000	1450	90	90	3000	1287	78	90				
113.4	3000	1466	90	90	3000	1288	79	90				
113.6	3000	1486	90	90	3000	1300	80	90				
113.8	3000	1498	90	90	3000	1314	80	90				
114	3000	1512	90	90	3000	1338	81	90				
114.2	3000	1533	90	90	3000	1353	81	90				
114.4	3000	1562	89	90	3000	1365	82	90				
114.6	3000	1594	89	90	3000	1369	82	90				
114.8	3000	1630	89	90	3000	1364	83	90				
115	3000	1666	88	90	3000	1350	83	90				
115.2	3000	1708	88	90	3000	1327	84	90				
115.4	3000	1745	87	90	3000	1295	84	90				
115.6	3000	1778	87	90	3000	1249	85	90				
115.8	3000	1807	86	90	3000	1204	85	90				
116	3000	1833	86	90	3000	1156	85	90				
116.2	3000	1854	85	90	3000	1119	85	90				
116.4	3000	1870	85	90	3000	1091	85	90				
116.6	3000	1880	84	90	3000	1072	86	90				
116.8	3000	1879	84	90	3000	1066	86	90				
117	3000	1865	83	90	3000	1074	86	90				
117.2	3000	1836	83	90	3000	1097	86	90				
117.4	3000	1796	82	90	3000	1132	87	90				
117.6	3000	1748	81	90	3000	1189	87	90				
117.8	3000	1700	81	90	3000	1258	87	90				
118	3000	1652	80	90	3000	1320	87	90				
118.2	3000	1605	80	90	3000	1386	87	90				
118.4	3000	1562	79	90	3000	1461	87	90				
118.6	3000	1513	78	90	3000	1523	87	90				
118.8	3000	1473	78	90	3000	1590	88	90				
119					3000	1650	88	90				
119.2					3000	1694	88	90				
119.4					3000	1734	88	90				
119.6					3000	1772	88	90				
119.8					3000	1800	88	90				
120					3000	1810	88	90				
120.2					3000	1785	88	90				
120.4					3000	1757	88	90				
120.6					3000	1722	88	90				
120.8					3000	1675	88	90				
121					3000	1631	88	90				
121.2					3000	1591	88	90				
121.4					3000	1557	88	90				
121.6					3000	1525	88	90				
121.8					3000	1490	88	90				
122					3000	1446	88	90				
122.2					3000	1406	88	90				
122.4					3000	1370	88	90				

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
122.6					3000	1336	88	90				
122.8					3000	1304	88	90				
123					3000	1283	88	90				
123.2					3000	1267	88	90				
123.4					3000	1255	88	90				
123.6					3000	1251	88	90				
123.8					3000	1251	88	90				
124					3000	1258	88	90				
124.2					3000	1265	88	90				
124.4					3000	1271	88	90				
124.6					3000	1277	88	90				
124.8					3000	1284	88	90				
125					3000	1290	88	90				
125.2					3000	1296	88	90				
125.4					3000	1303	88	90				
125.6					3000	1310	88	90				
125.8					3000	1316	88	90				
126					3000	1323	88	90				
126.2					3000	1327	88	90				
126.4					3000	1325	88	90				
126.6					3000	1311	88	90				
126.8					3000	1284	88	90				
127					3000	1245	89	90				
127.2					3000	1194	89	90				
127.4					3000	1129	89	90				
127.6					3000	1050	89	90				
127.8					3000	956	89	90				
128					3000	847	89	90				
128.2					3000	726	89	90				
128.4					3000	592	89	90				
128.6					3000	453	89	90				
128.8					3000	311	89	90				
129					3000	179	89	90				
129.2					3000	64	90	90				
129.4					3000	-23	90	90				
129.6					3000	-75	90	90				
129.8					3000	-88	90	90				
130					3000	-57	90	90				
130.2					3000	16	90	90				
130.4					3000	132	90	90				
130.6					3000	288	91	90				
130.8					3000	507	91	90				
131					3000	715	91	90				
131.2					3000	929	91	90				
131.4					3000	1143	91	90				
131.6					3000	1351	91	90				
131.8					3000	1542	91	90				
132					3000	1715	91	90				
132.2					3000	1859	91	90				

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
132.4					3000	1967	91	90				
132.6					3000	2037	91	90				
132.8					3000	2064	91	90				
133					3000	2052	91	90				
133.2					3000	2007	91	90				
133.4					3000	1887	91	90				
133.6					3000	1733	91	90				
133.8					3000	1569	91	90				
134					3000	1405	91	90				
134.2					3000	1246	91	90				
134.4					3000	1099	91	90				
134.6					3000	969	92	90				
134.8					3000	859	92	90				
135					3000	764	92	90				
135.2					3000	714	92	90				
135.4					3000	696	92	90				
135.6					3000	718	92	90				
135.8					3000	772	92	90				
136					3000	855	92	90				
136.2					3000	963	92	90				
136.4					3000	1093	92	90				
136.6					3000	1240	92	90				
136.8					3000	1398	92	90				
137					3000	1556	92	90				
137.2					3000	1703	92	90				
137.4					3000	1832	92	90				
137.6					3000	1937	92	90				
137.8					3000	2013	93	90				
138					3000	2061	93	90				
138.2					3000	2081	93	90				
138.4					3000	2076	93	90				
138.6					3000	2045	93	90				
138.8					3000	1989	93	90				
139					3000	1911	93	90				
139.2					3000	1799	93	90				
139.4					3000	1679	93	90				
139.6					3000	1532	93	90				
139.8					3000	1406	93	90				
140					3000	1276	94	90				
140.2					3000	1146	94	90				
140.4					3000	1019	94	90				
140.6					3000	876	94	90				
140.8					3000	764	94	90				
141					3000	650	94	90				
141.2					3000	572	93	90				
141.4					3000	517	93	90				
141.6					3000	487	93	90				
141.8					3000	497	92	90				
142					3000	541	91	90				

Appendix C: (Continued)

Table C.4 (Continued)

	NDBW				GB/s				Joystick			
Time	Width	Position	Speed	Posted	Width	Position	Speed	Posted	Width	Position	Speed	Posted
142.2					3000	617	91	90				
142.4					3000	723	90	90				
142.6					3000	849	90	90				
142.8					3000	985	89	90				
143					3000	1120	88	90				
143.2					3000	1239	88	90				
143.4					3000	1333	87	90				
143.6					3000	1397	87	90				
143.8					3000	1431	86	90				

Appendix C: (Continued)

The following graphs show the steering results for each participant with respect to time.

Group 1, Participant 1: (Age 36, Right-Handed, Does not use DBW controls)

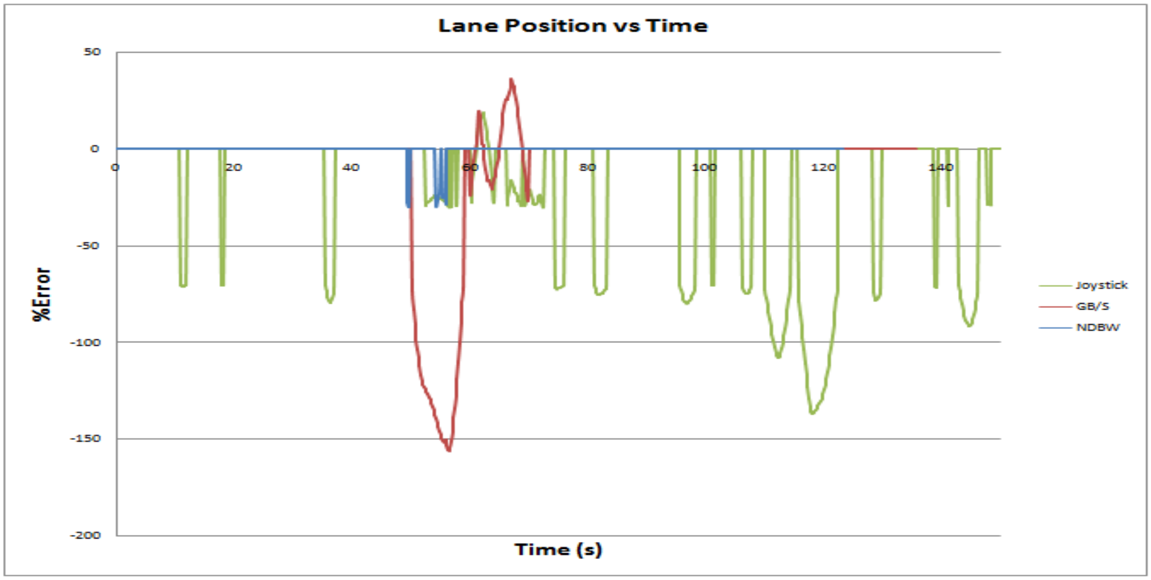


Figure C.1 - Steering Results, Participant 1

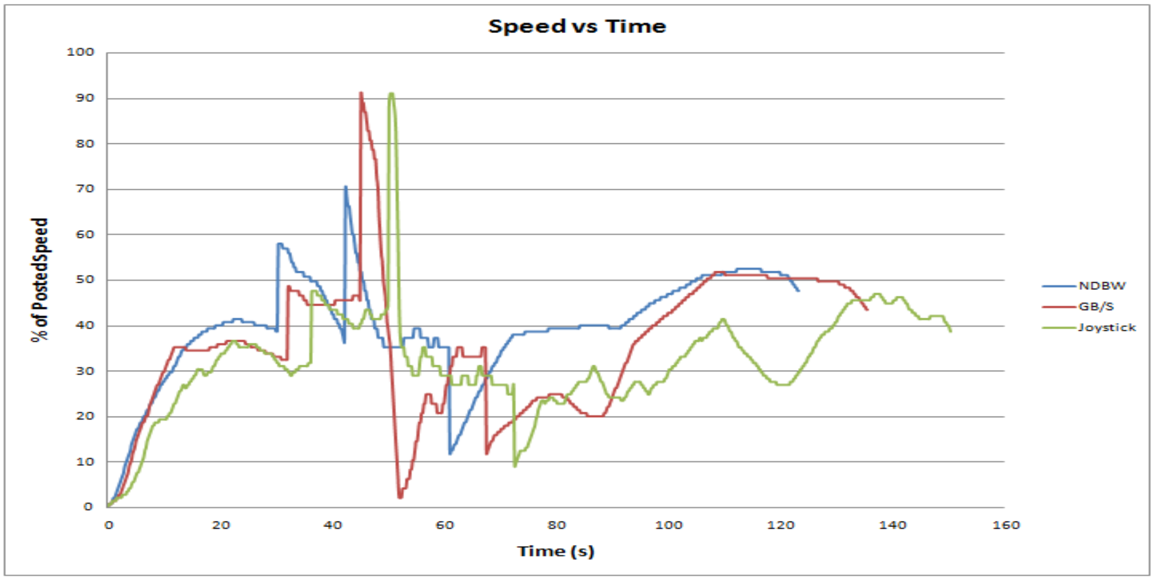


Figure C.2 – Speed Results, Participant 1

Appendix C: (Continued)

Group 1, Participant 2: (Age 25, Right-Handed, Does not use DBW controls)

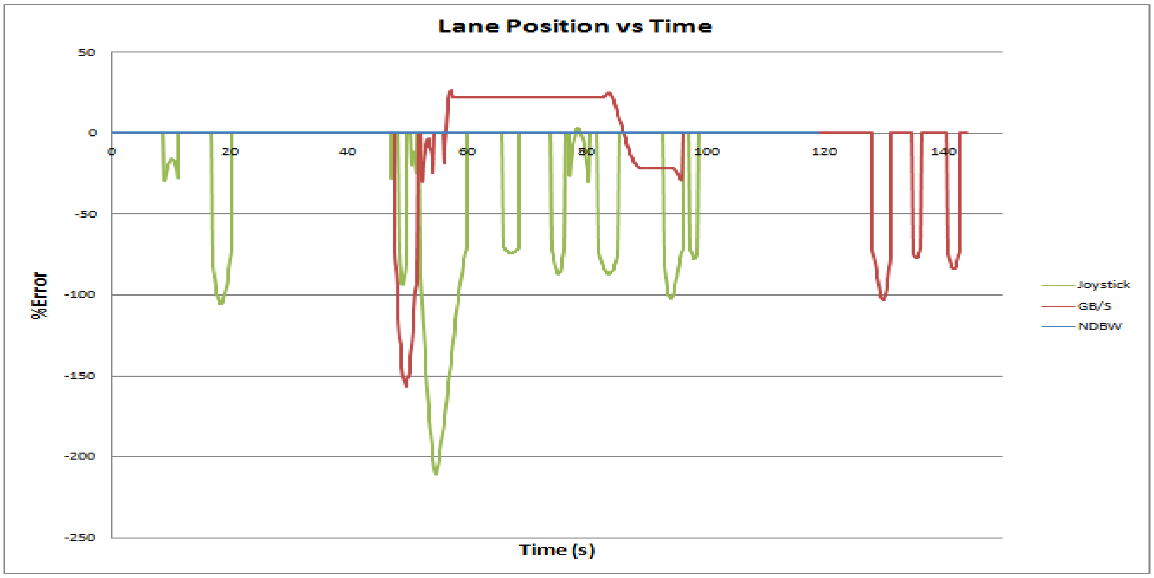


Figure C.3 - Steering Results, Participant 2

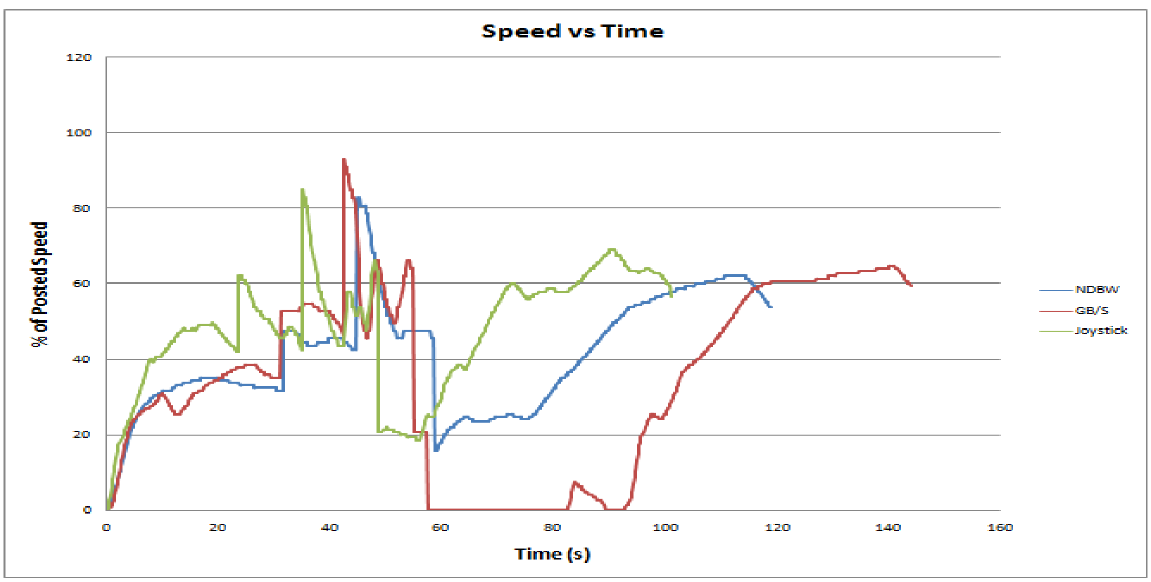


Figure C.4 - Speed Results, Participant 2

Appendix C: (Continued)

Group 1, Participant 3: (Age 24, Right-Handed, Does not use DBW controls)

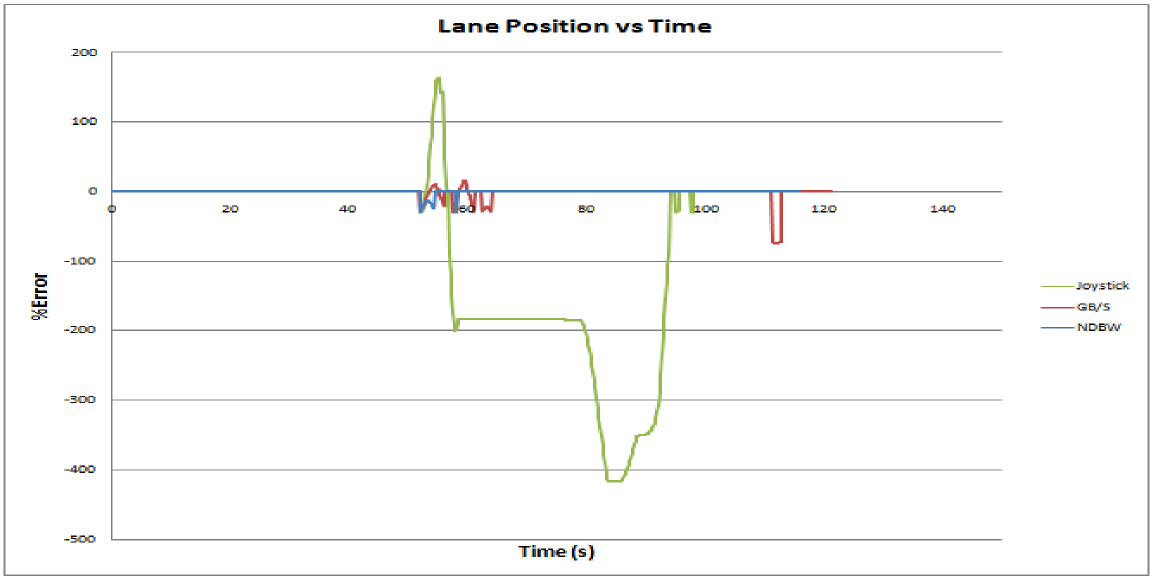


Figure C.5 - Steering Results, Participant 3

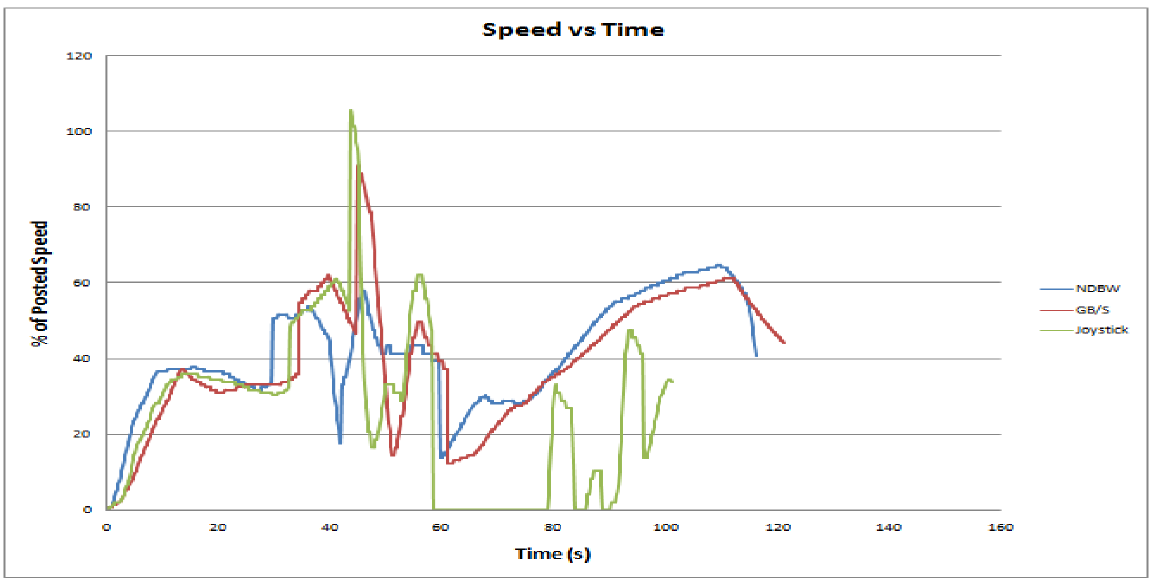


Figure C.6 - Speed Results, Participant 3

Appendix C: (Continued)

Group 1, Participant 4: (Age 25, Right-Handed, Does not use DBW controls)

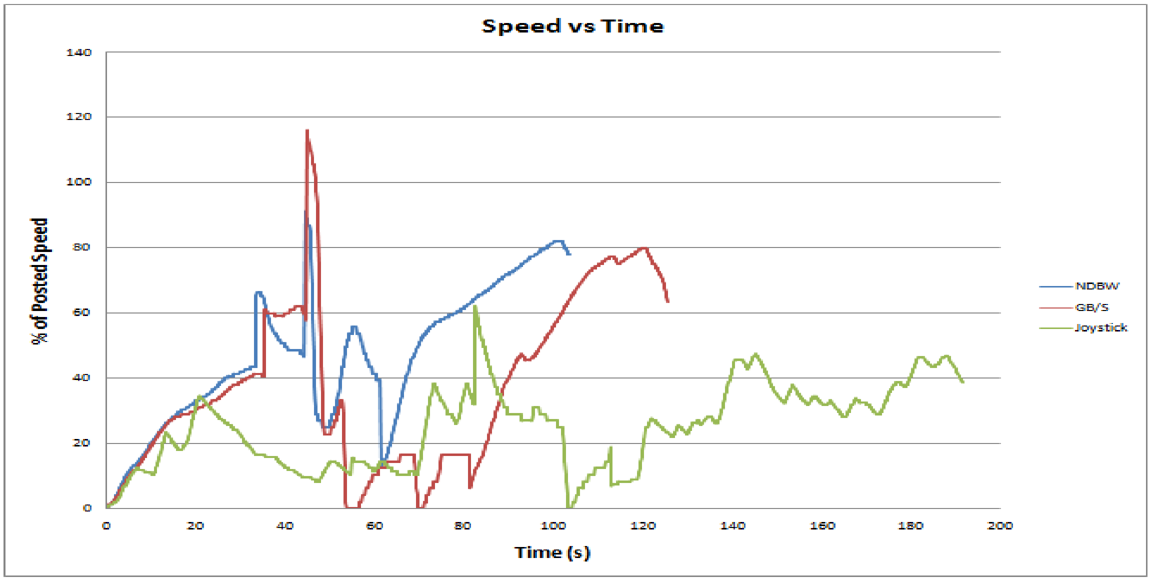


Figure C.7 - Steering Results, Participant 4

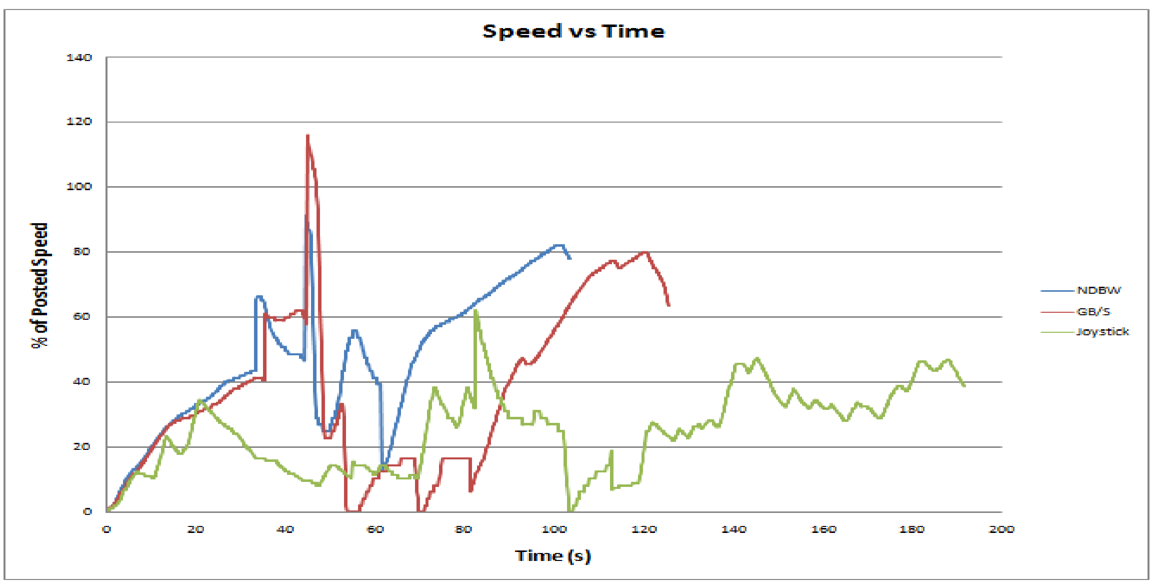


Figure C.8 - Speed Results, Participant 4

Appendix C: (Continued)

Group 1, Participant 5: (Age 35, Right-Handed, Does not use DBW controls)

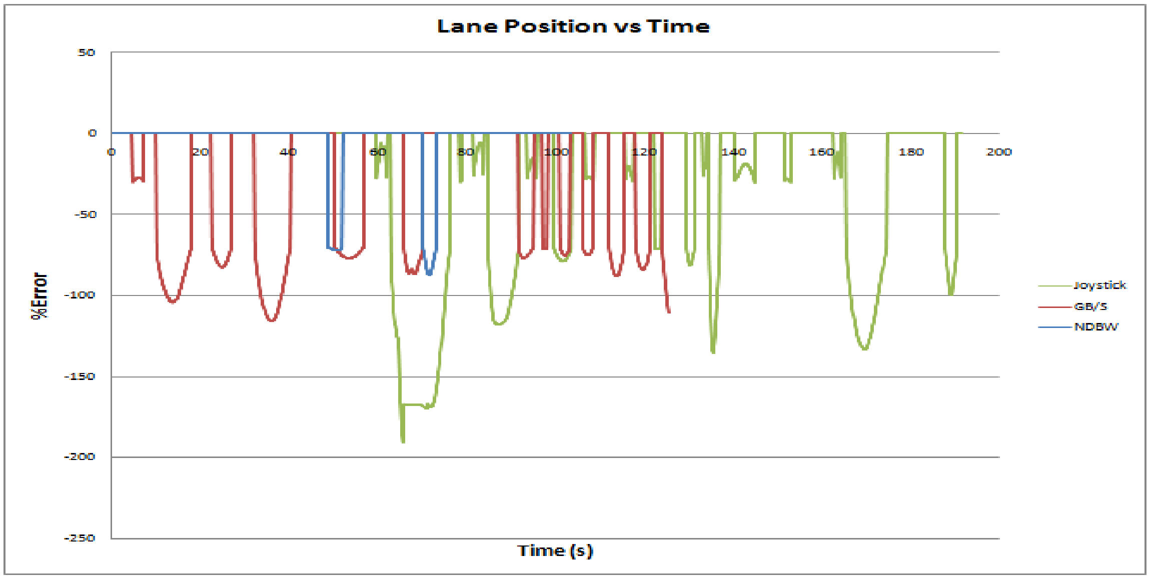


Figure C.9 - Steering Results, Participant 5

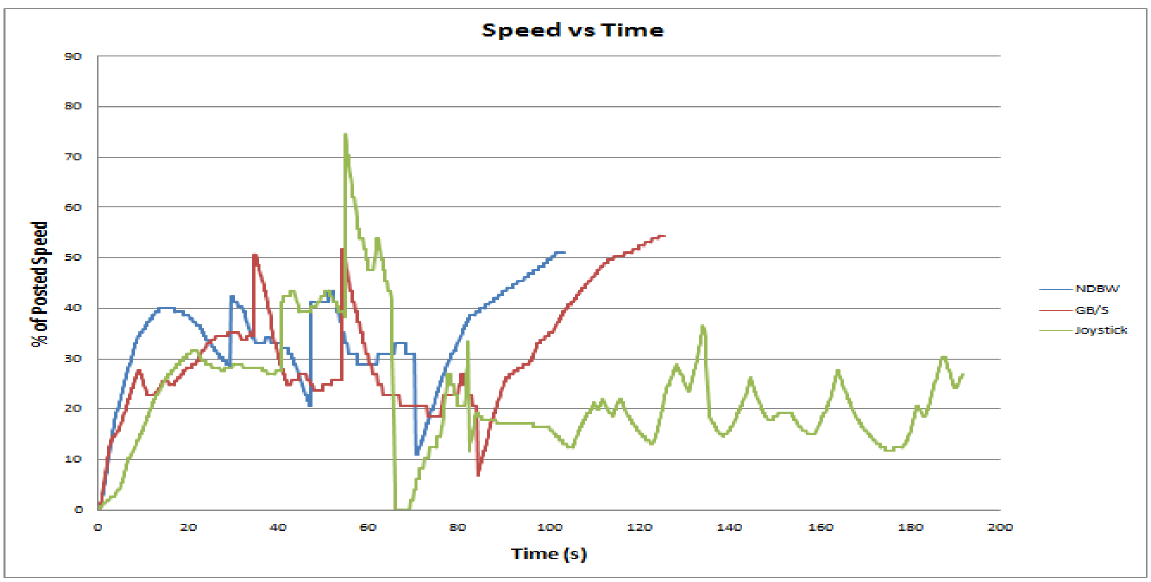


Figure C.10 – Speed Results, Participant 5

Appendix C: (Continued)

Group 1, Participant 6: (Age 40, Right-Handed, Does not use DBW controls)

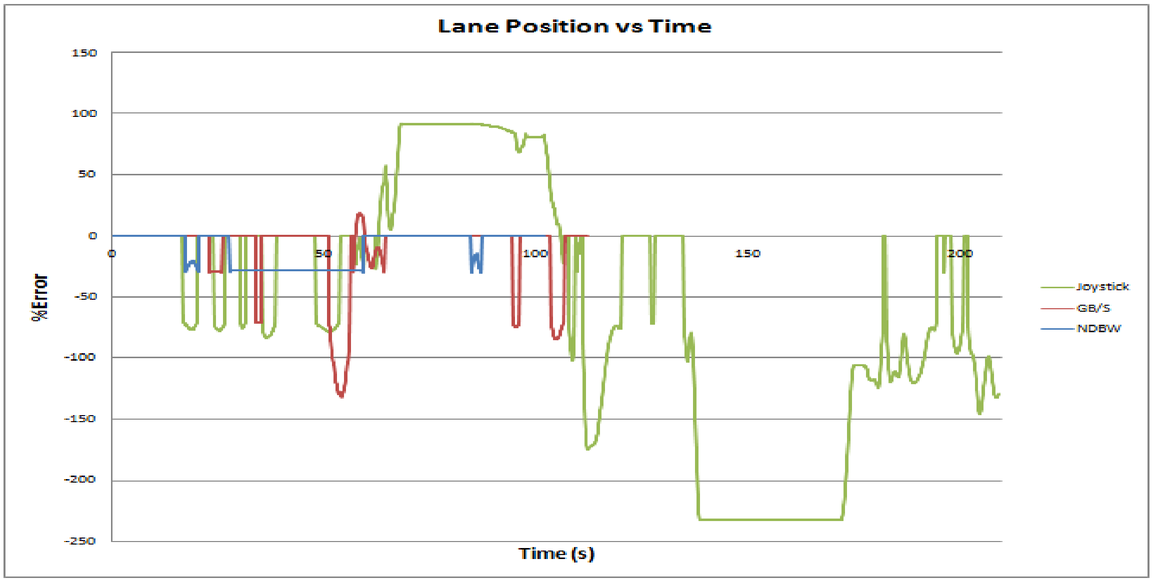


Figure C.11 - Steering Results, Participant 6

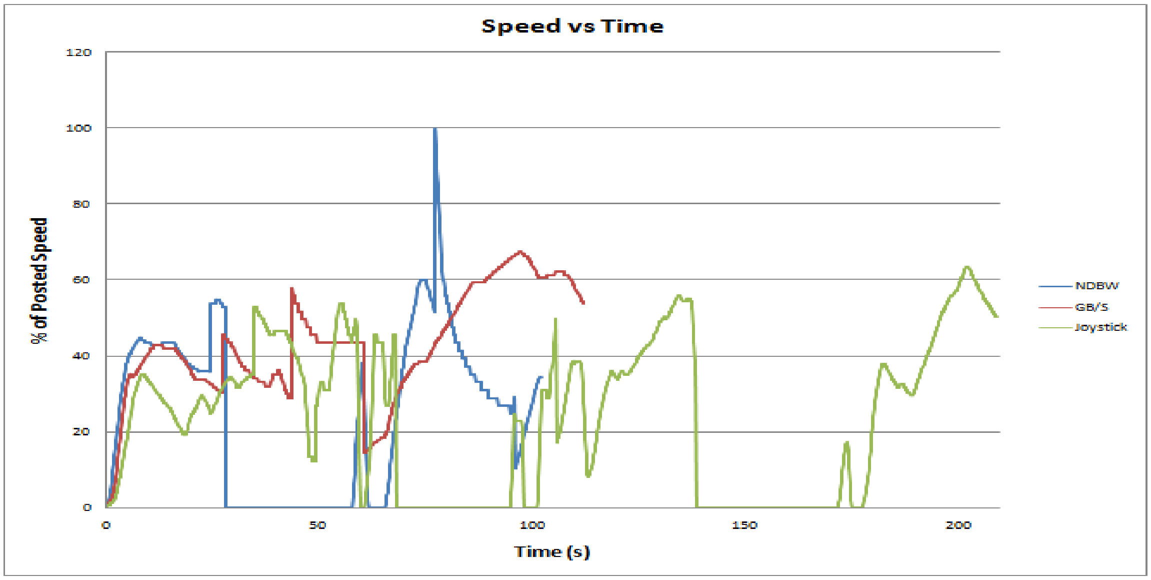


Figure C.12 – Speed Results, Participant 6

Appendix C: (Continued)

Group 1, Participant 7: (Age 23, Right-Handed, Does not use DBW controls)

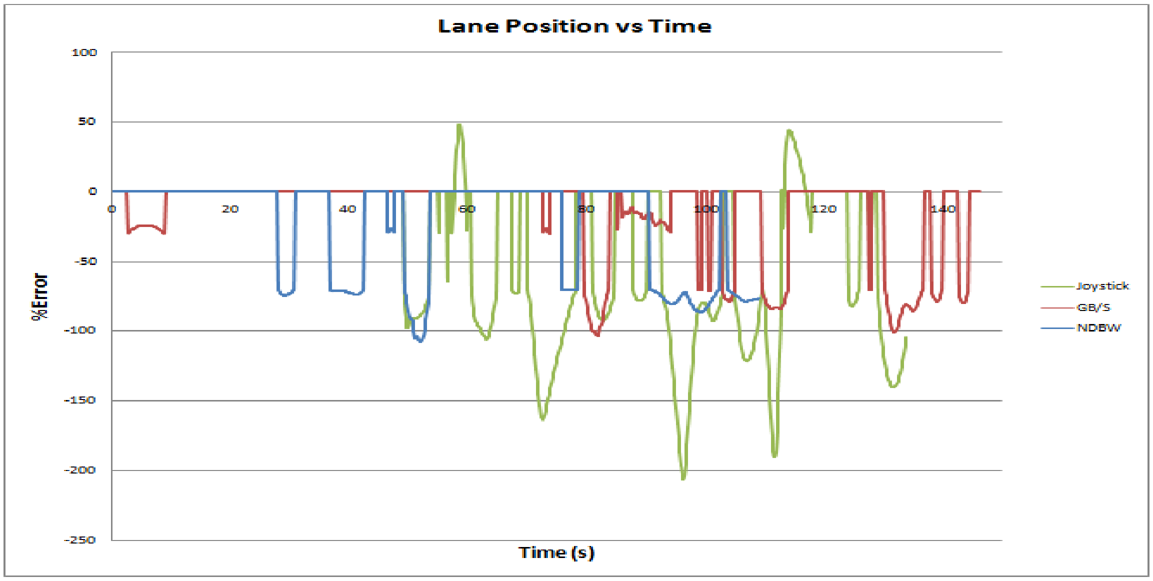


Figure C.13 - Steering Results, Participant 7

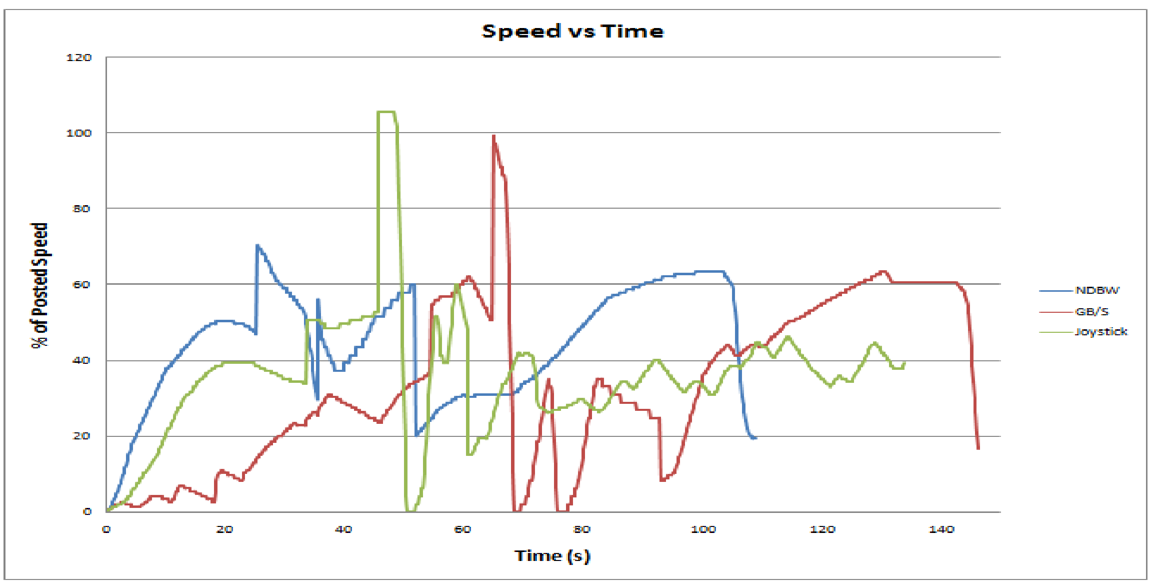


Figure C.14 – Speed Results, Participant 7

Appendix C: (Continued)

Group 1, Participant 8: (Age 54, Left-Handed, Does not use DBW controls)

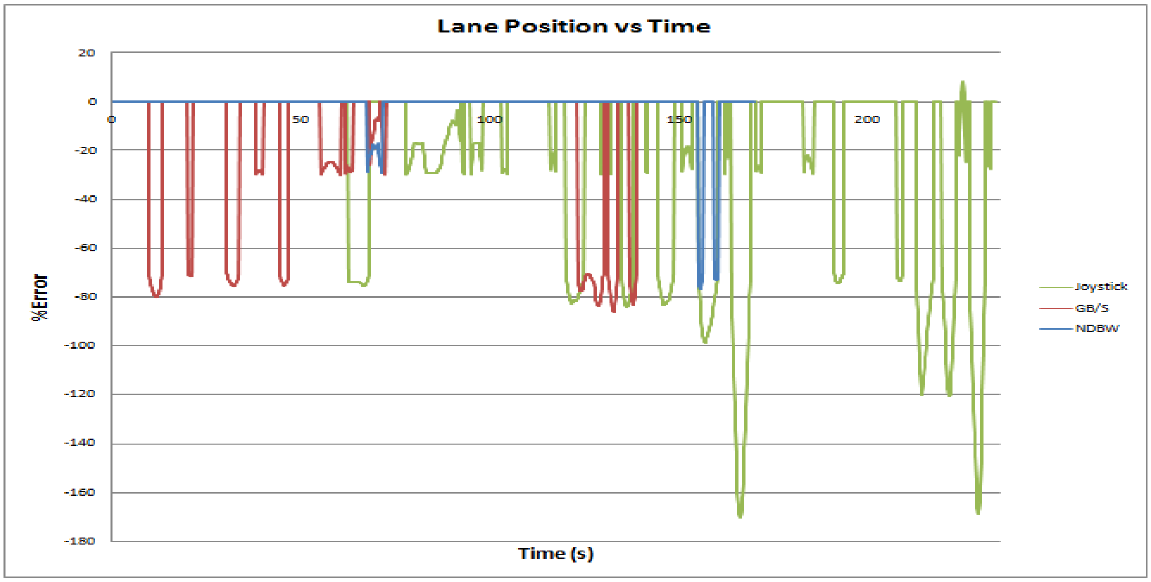


Figure C.15 - Steering Results, Participant 8

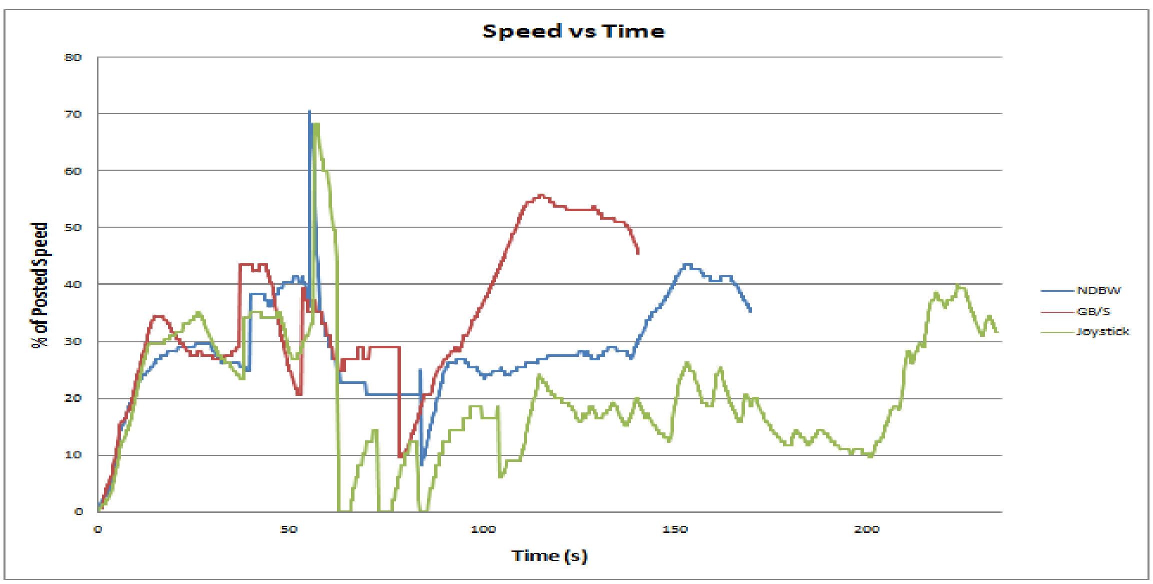


Figure C.16 – Speed Results, Participant 8

Appendix C: (Continued)

Group 1, Participant 9: (Age 48, Right-Handed, Does not use DBW controls)

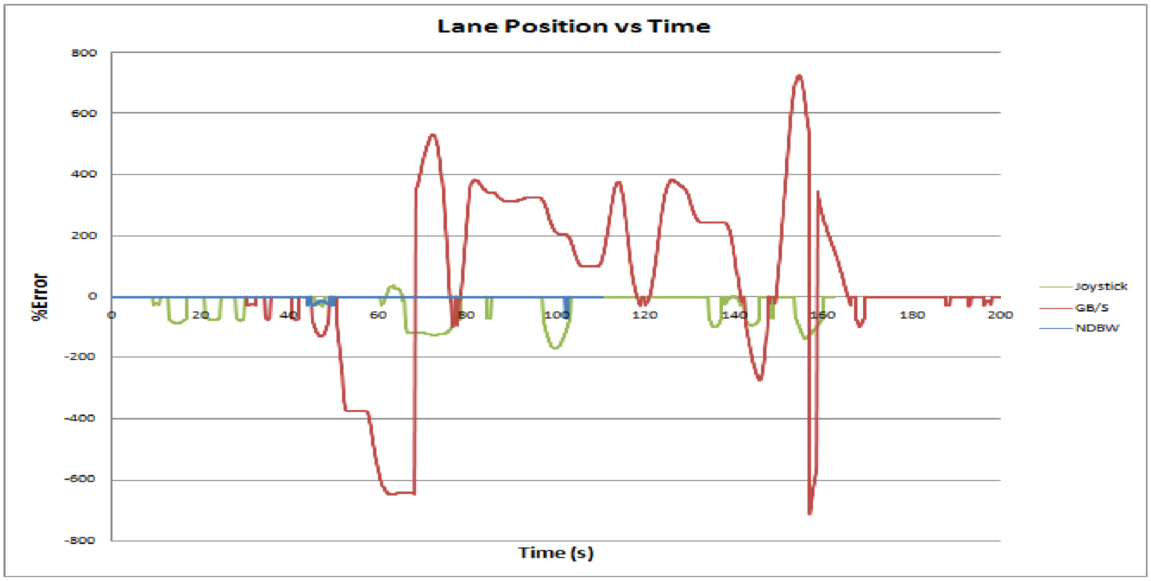


Figure C.17 - Steering Results, Participant 9

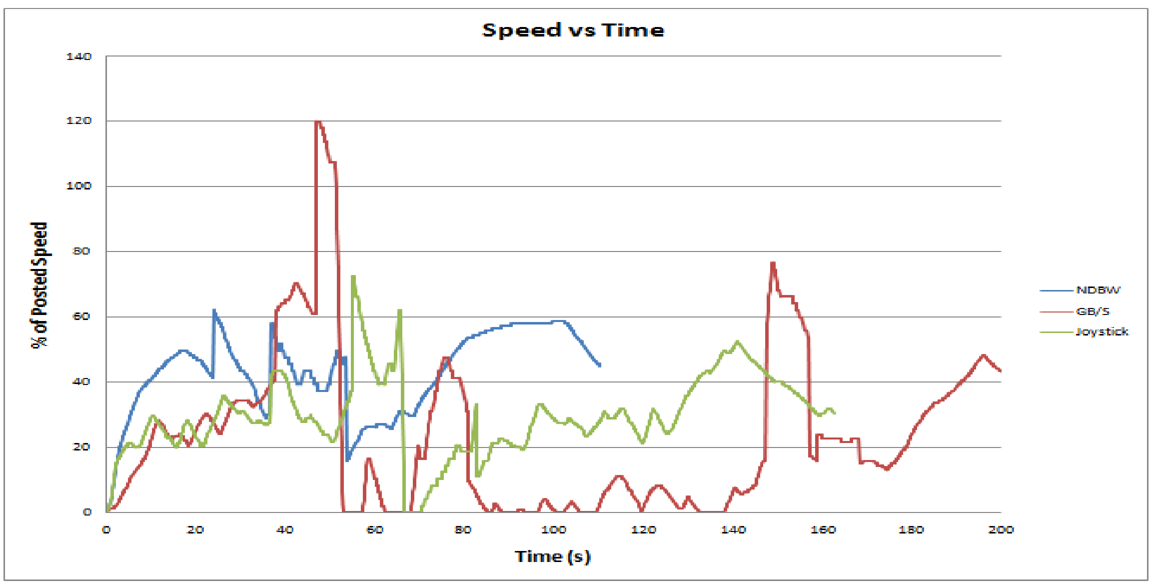


Figure C.18 – Speed Results, Participant 9

Appendix C: (Continued)

Group 1, Participant 10: (Age 50, Right-Handed, Does not use DBW controls)

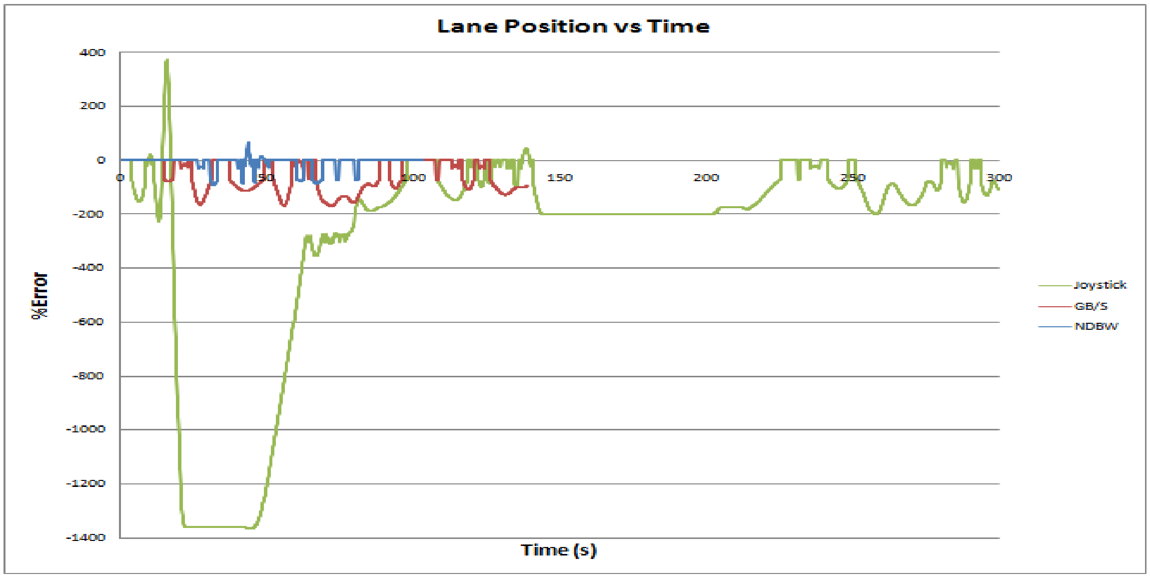


Figure C.19 - Steering Results, Participant 10

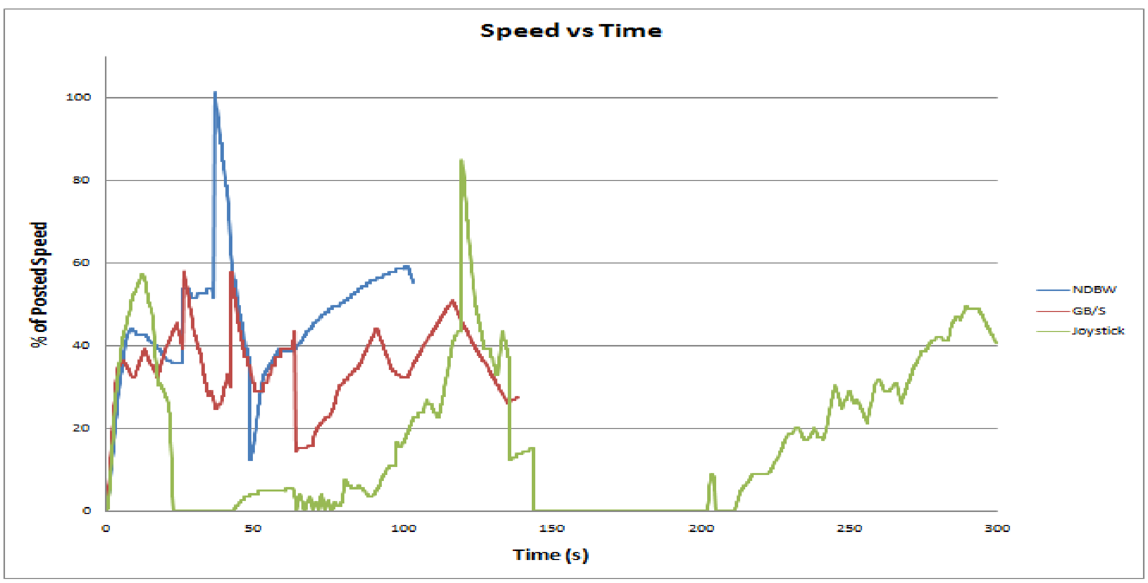


Figure C.20 – Speed Results, Participant 10

Appendix C: (Continued)

C.3. Steering Data for Elderly Drivers

Group 2, Participant 11: (Age 79, Right-Handed, Does not use DBW controls)

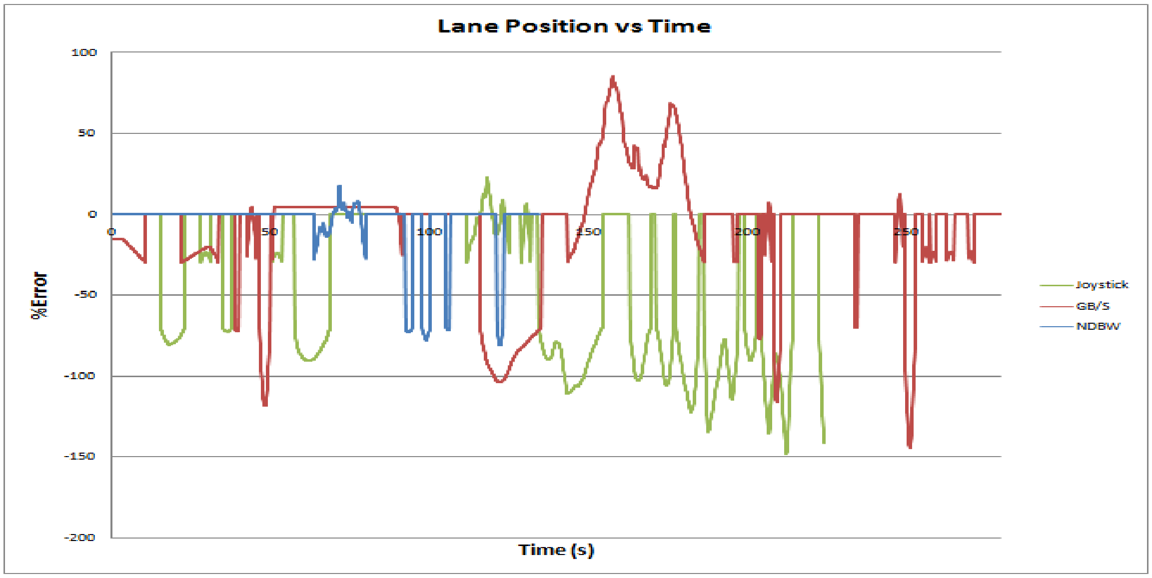


Figure C.21 - Steering Results, Participant 11

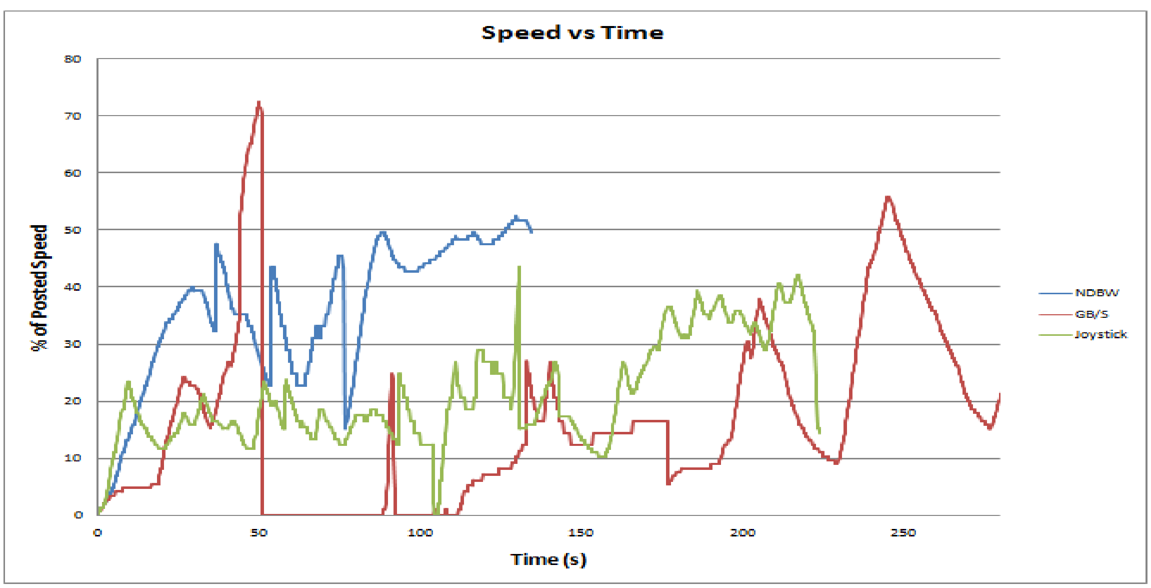


Figure C.22 – Speed Results, Participant 11

Appendix C: (Continued)

Group 2, Participant 12: (Age 71, Right-Handed, Does not use DBW controls)

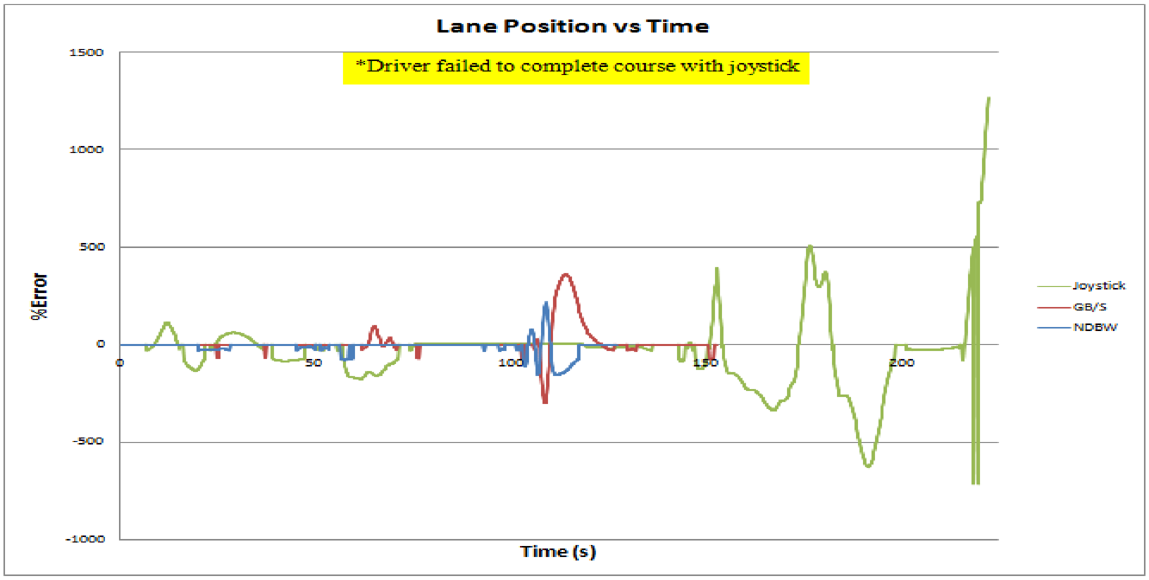


Figure C.23 - Steering Results, Participant 12

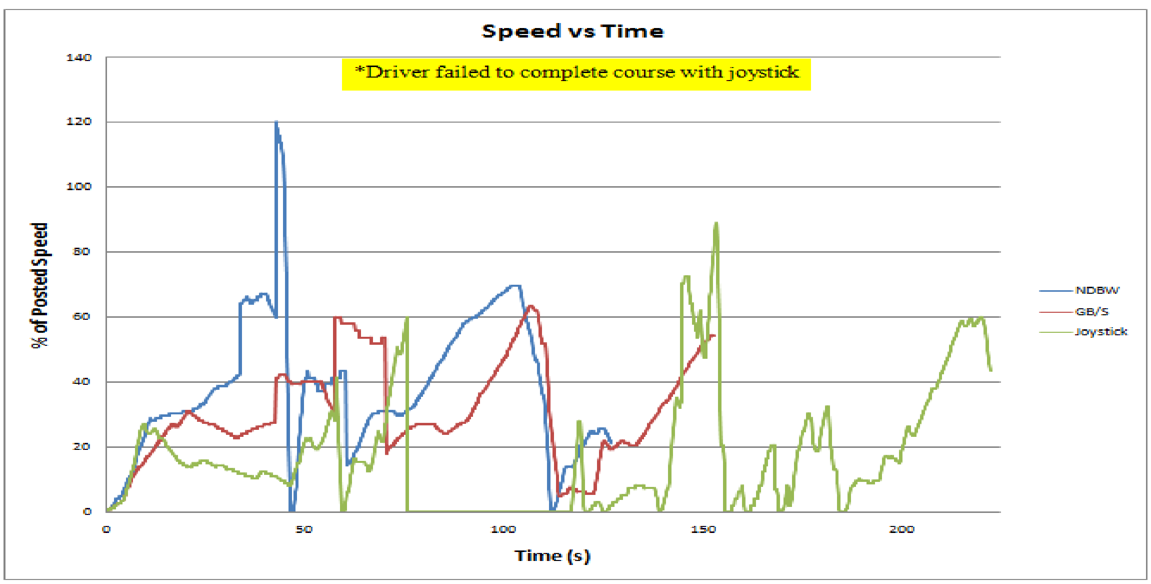


Figure C.24 – Speed Results, Participant 12

Appendix C: (Continued)

Group 2, Participant 13: (Age 73, Right-Handed, Does not use DBW controls)

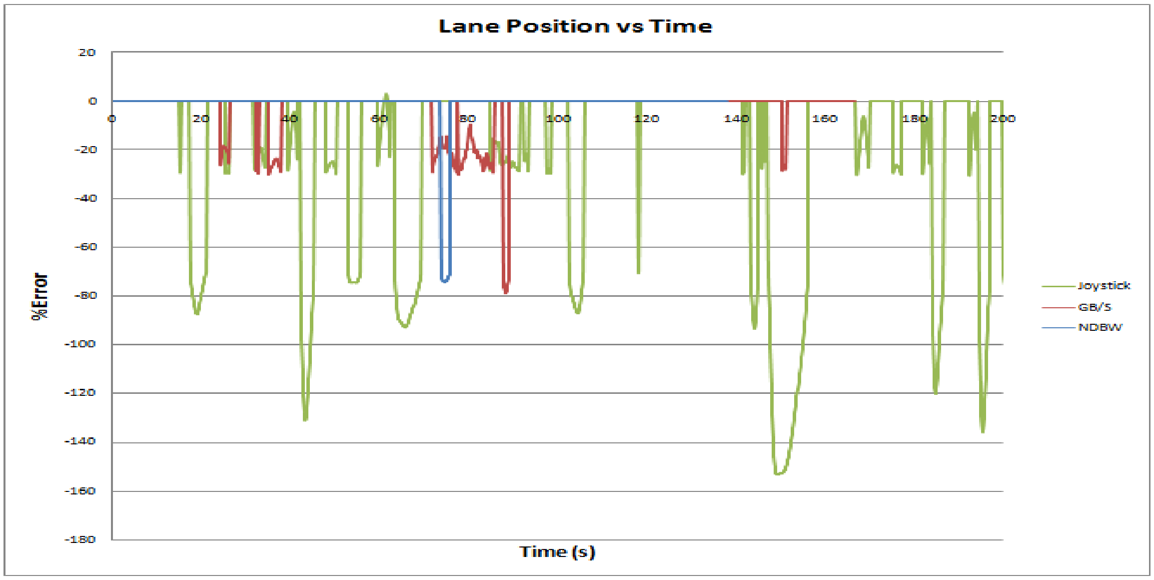


Figure C.25 - Steering Results, Participant 13

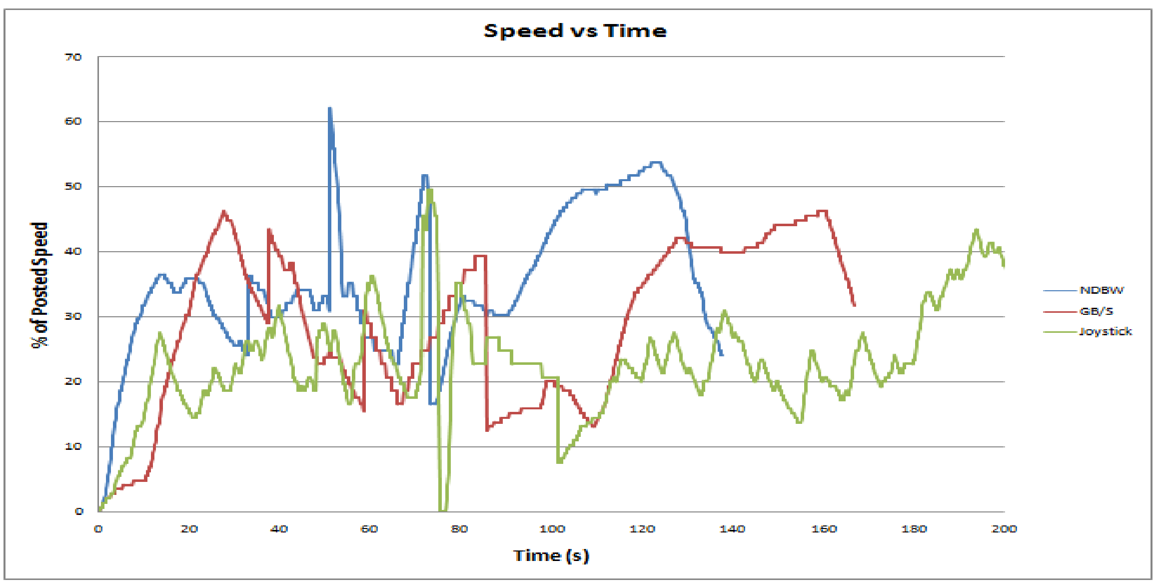


Figure C.26 – Speed Results, Participant 13

Appendix C: (Continued)

Group 2, Participant 14: (Age 65, Left-Handed, Does not use DBW controls)

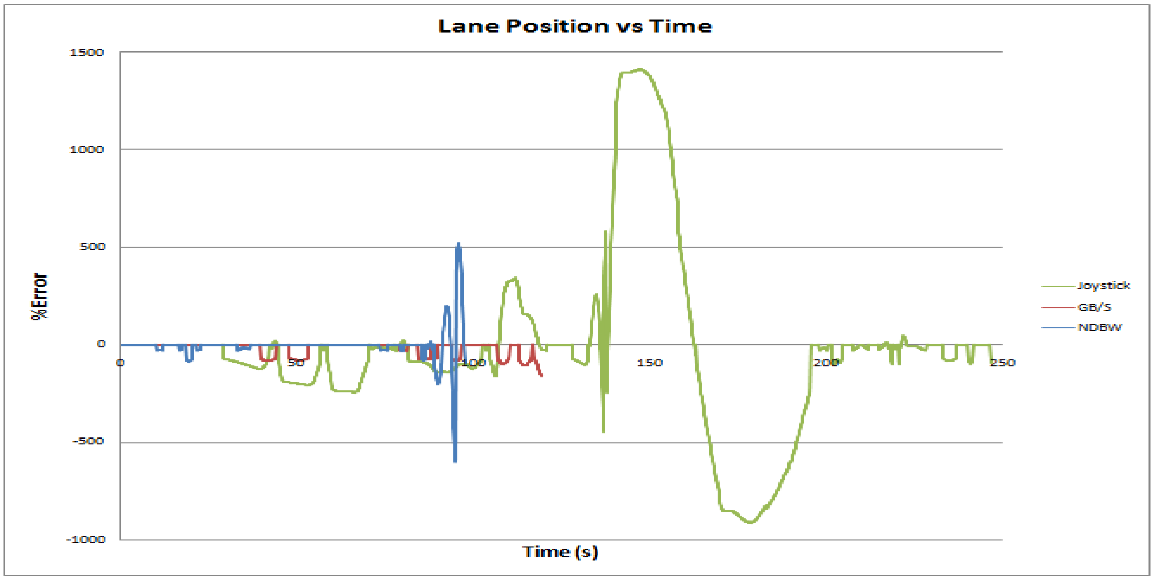


Figure C.27 - Steering Results, Participant 14

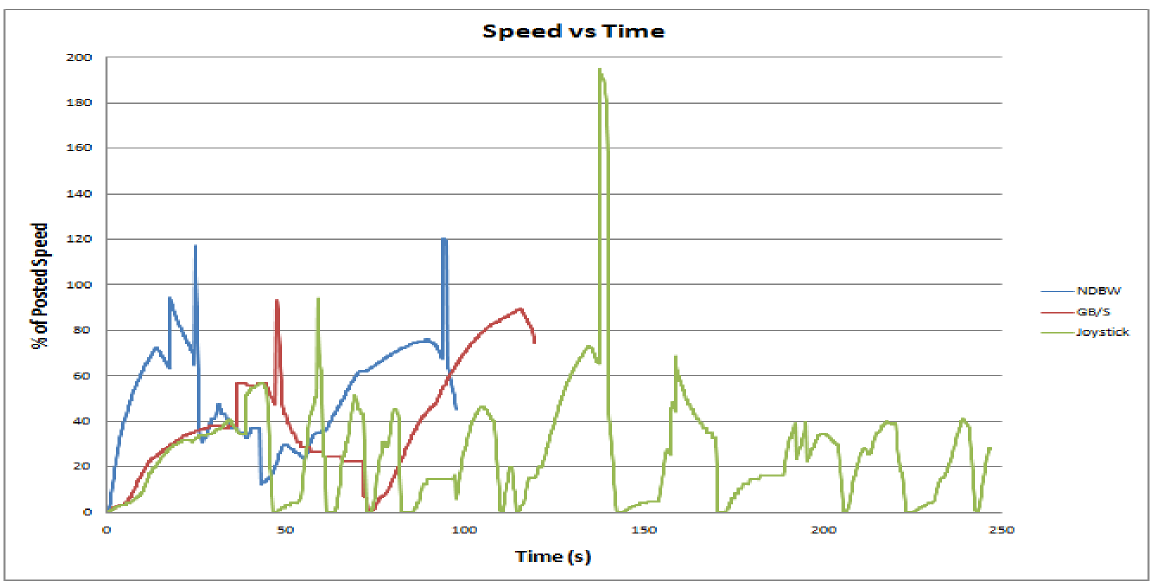


Figure C.28 – Speed Results, Participant 14

Appendix C: (Continued)

Group 2, Participant 15: (Age 69, Right-Handed, Does not use DBW controls)

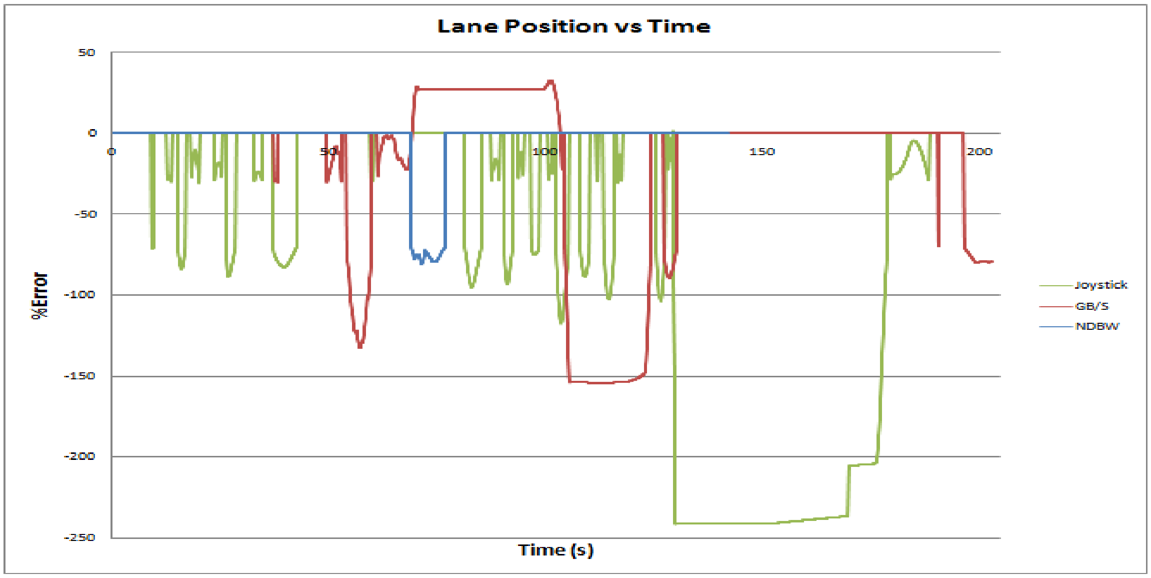


Figure C.29 - Steering Results, Participant 15

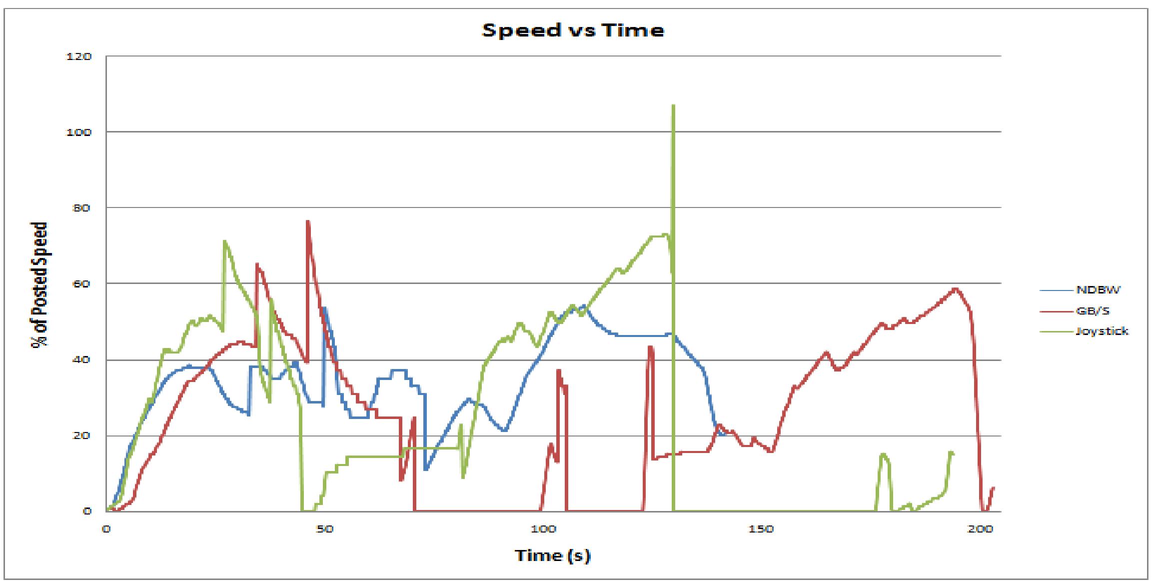


Figure C.30 – Speed Results, Participant 15

Appendix C: (Continued)

Group 2, Participant 16: (Age 67, Right-Handed, Does not use DBW controls)

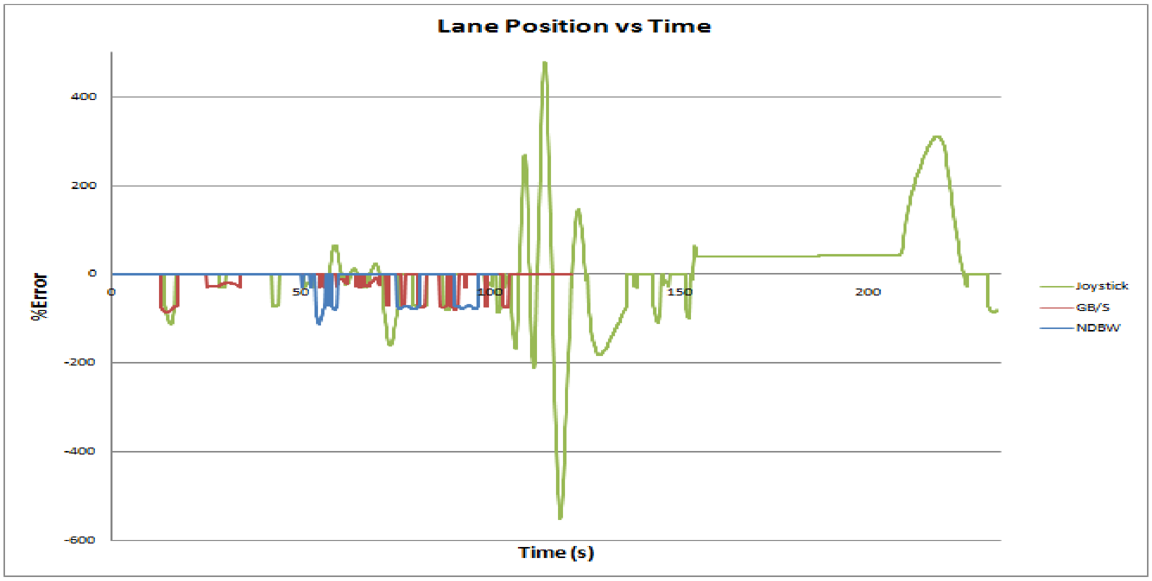


Figure C.31 - Steering Results, Participant 16

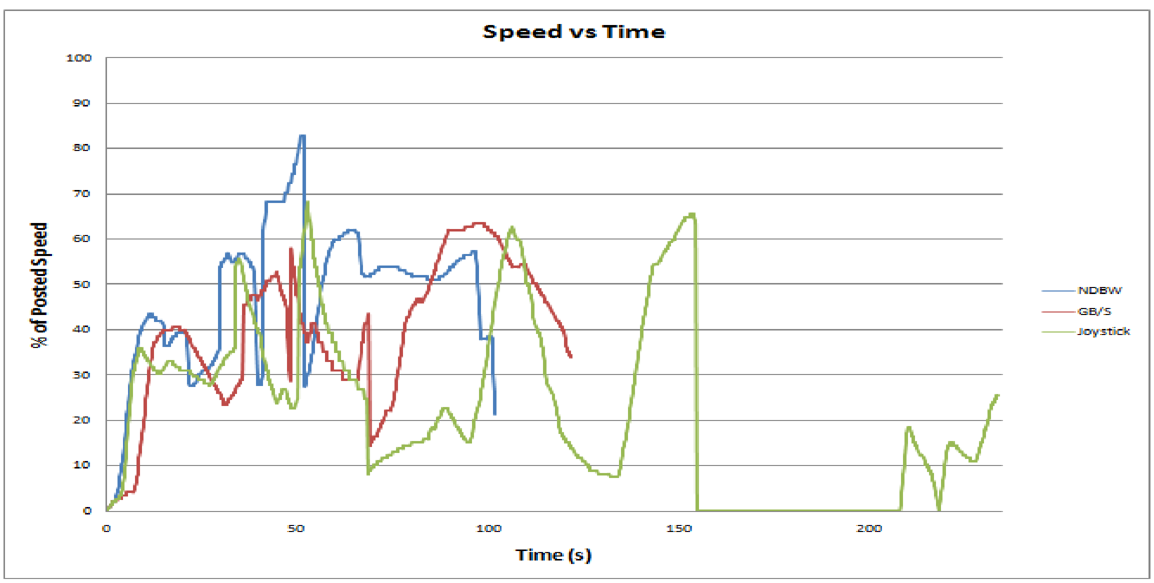


Figure C.32 – Speed Results, Participant 16

Appendix C: (Continued)

Group 2, Participant 17: (Age 75, Right-Handed, Does not use DBW controls)

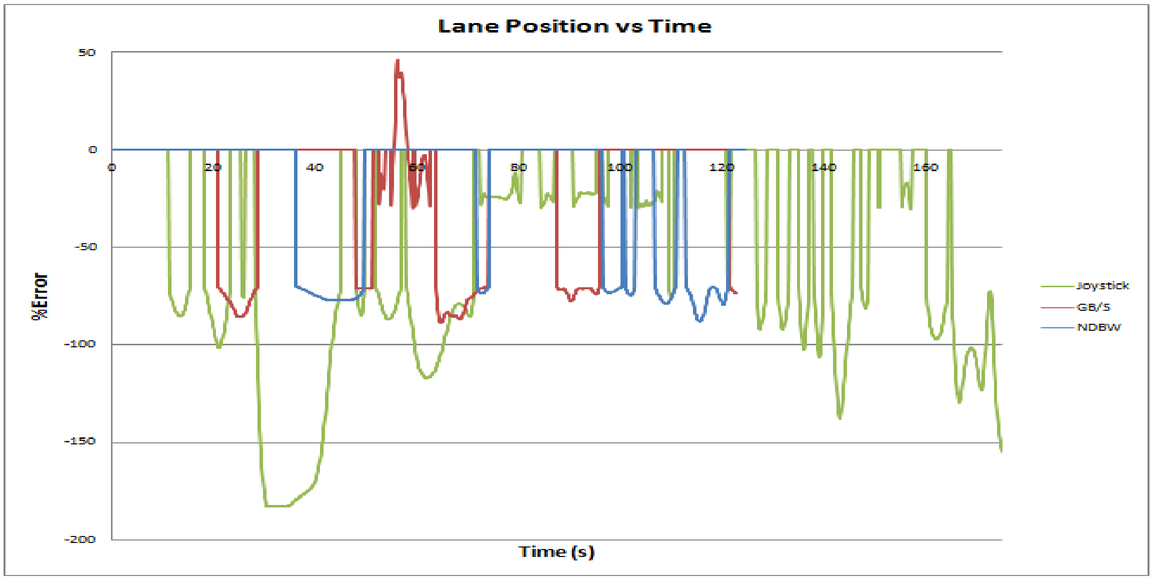


Figure C.33 - Steering Results, Participant 17

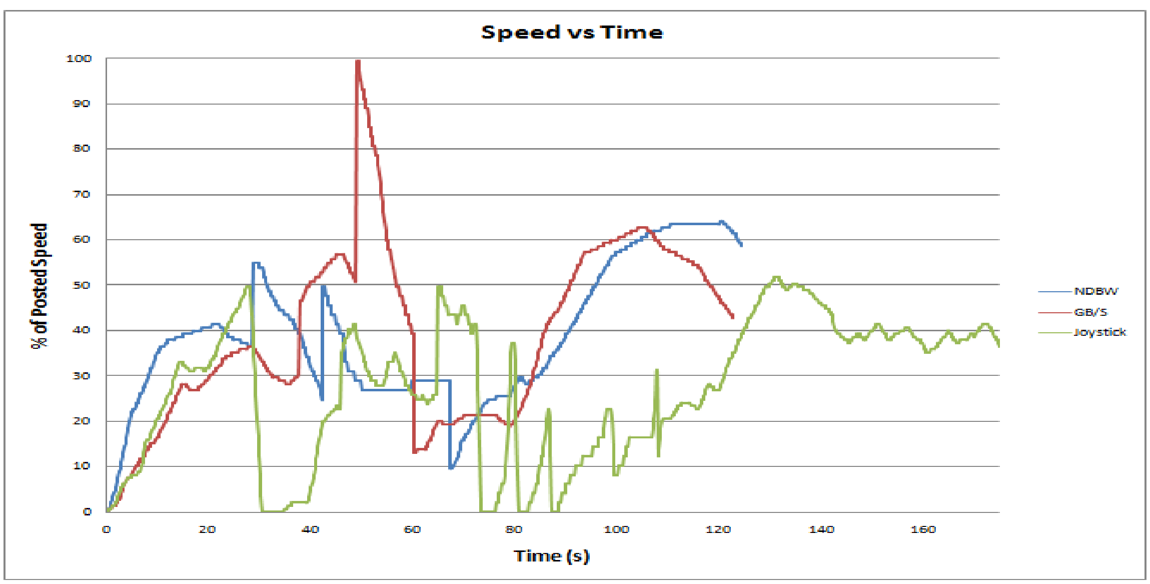


Figure C.34 – Speed Results, Participant 17

Appendix C: (Continued)

Group 2, Participant 18: (Age 72, Right-Handed, Does not use DBW controls)

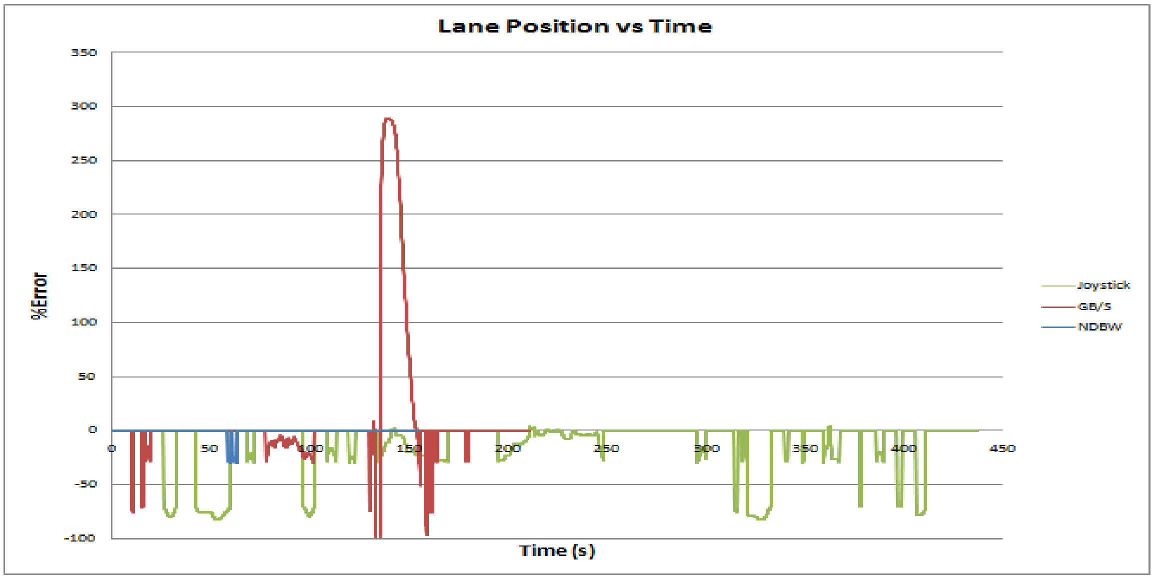


Figure C.35 - Steering Results, Participant 18

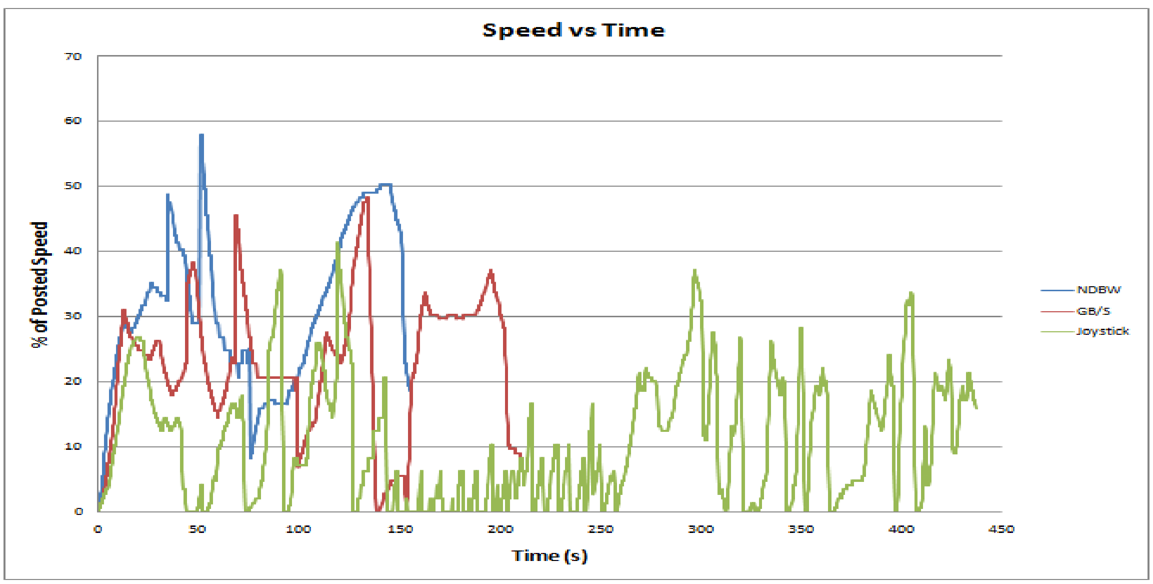


Figure C.36 – Speed Results, Participant 18

Appendix C: (Continued)

Group 2, Participant 19: (Age 69, Right-Handed, Does not use DBW controls)

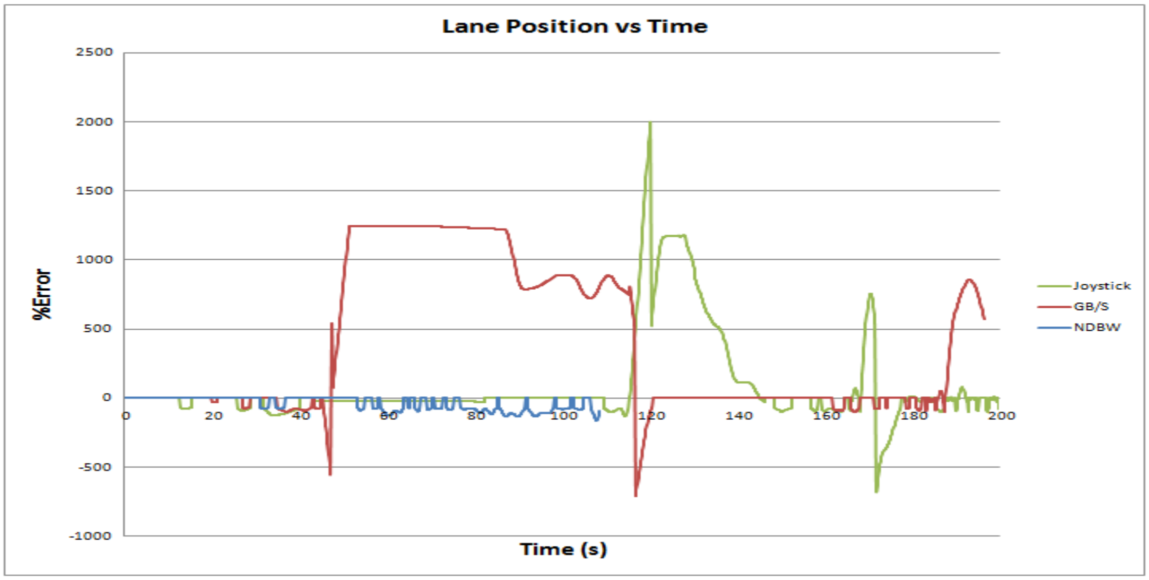


Figure C.37 - Steering Results, Participant 19

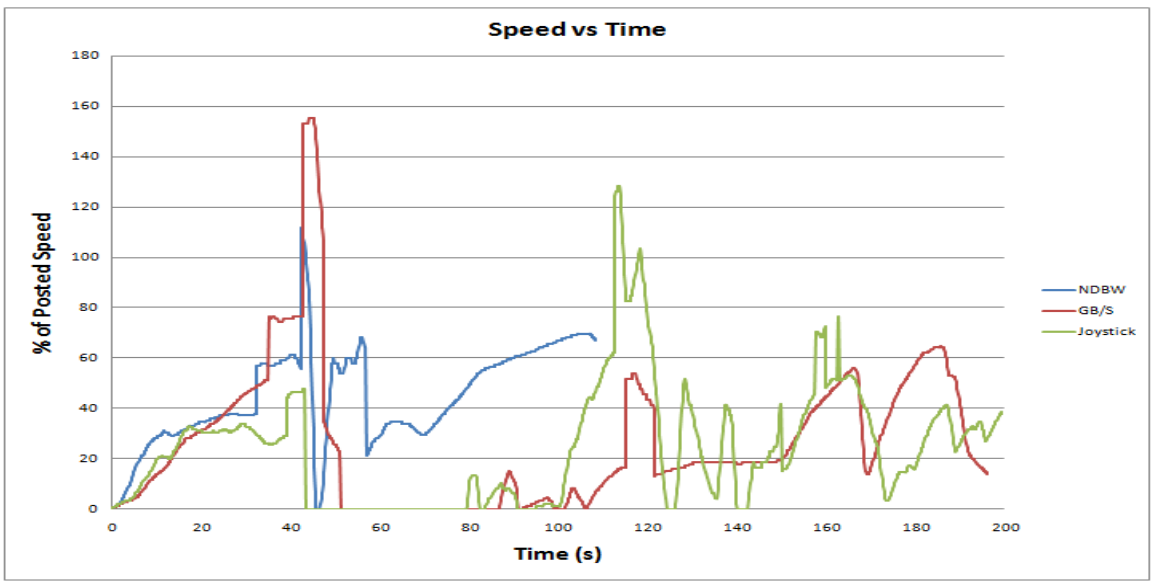


Figure C.38 - Speed Results, Participant 19

Appendix C: (Continued)

Group 2, Participant 20: (Age 80, Right-Handed, Does not use DBW controls)

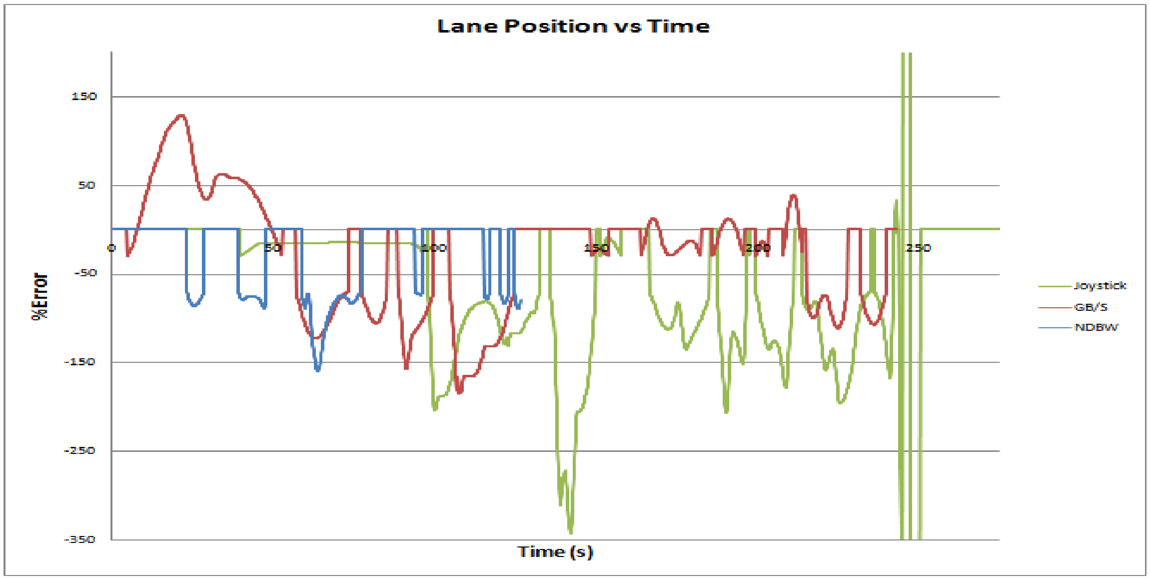


Figure C.39 - Steering Results, Participant 20

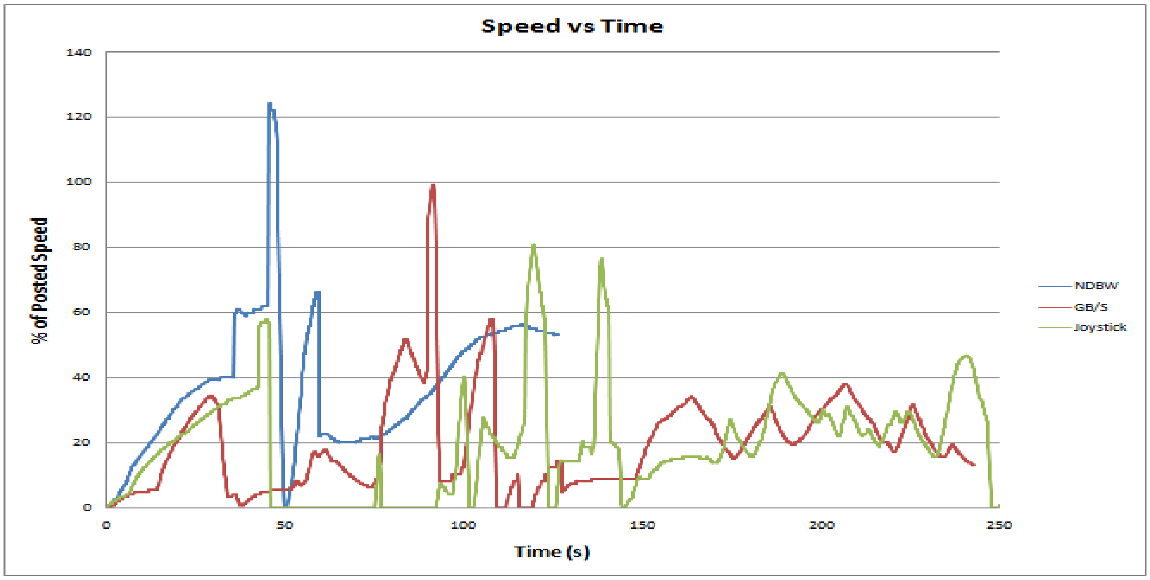


Figure C.40 – Speed Results, Participant 20

C.4. Steering Data for Drivers with Disabilities

Group 3, Participant 21: (Age 19, Right-Handed, Does Use Mechanical Hand Controls)

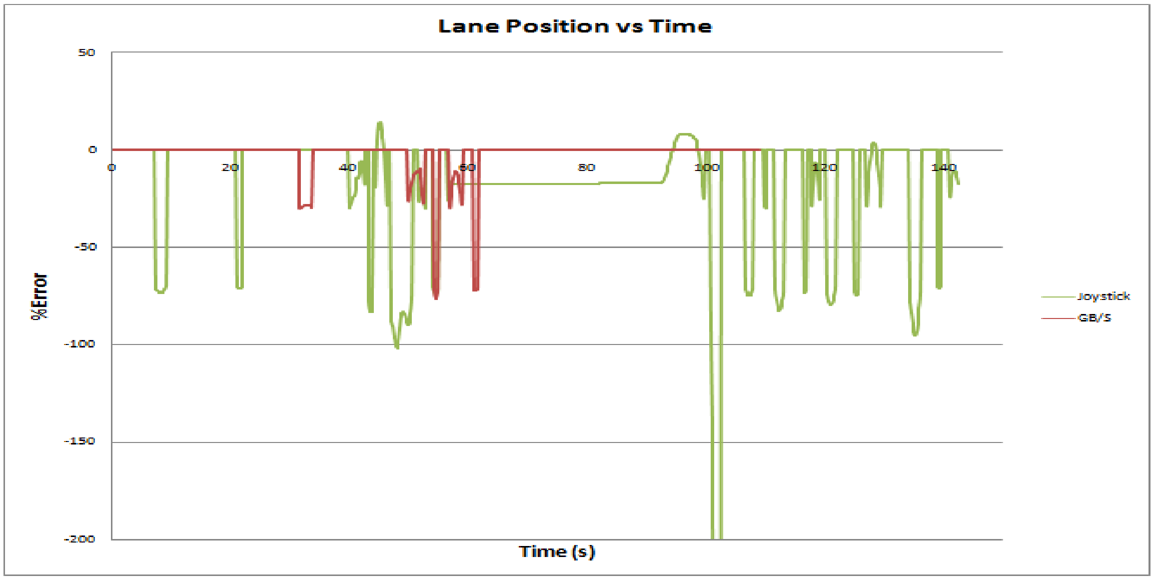


Figure C.41 - Steering Results, Participant 21

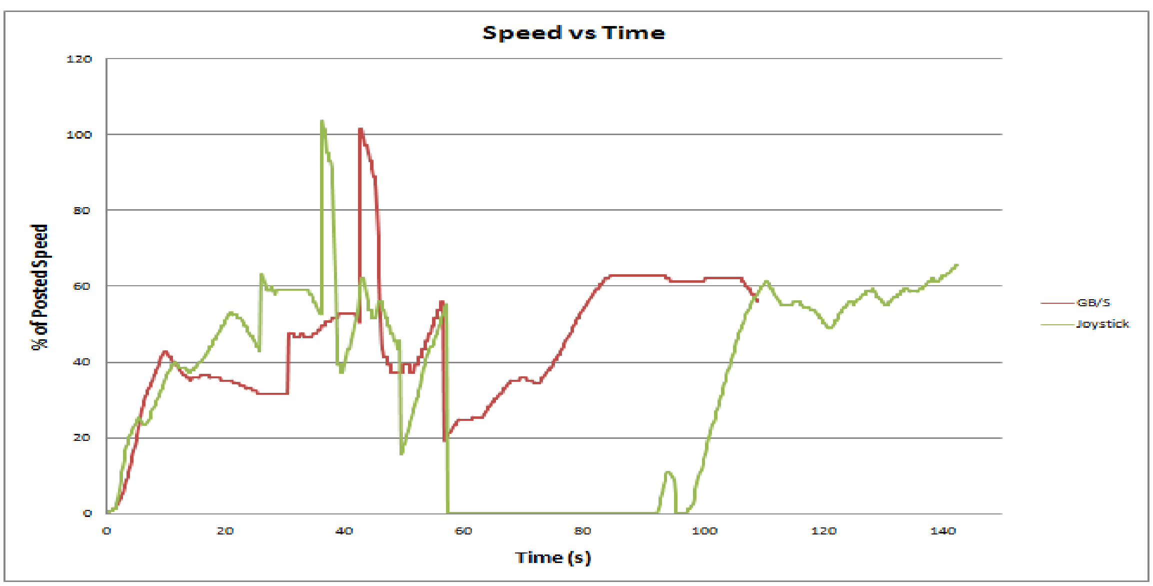


Figure C.42 – Speed Results, Participant 21

Group 3, Participant 22: (Age 58, Right-Handed, Does Use Mechanical Hand Controls)

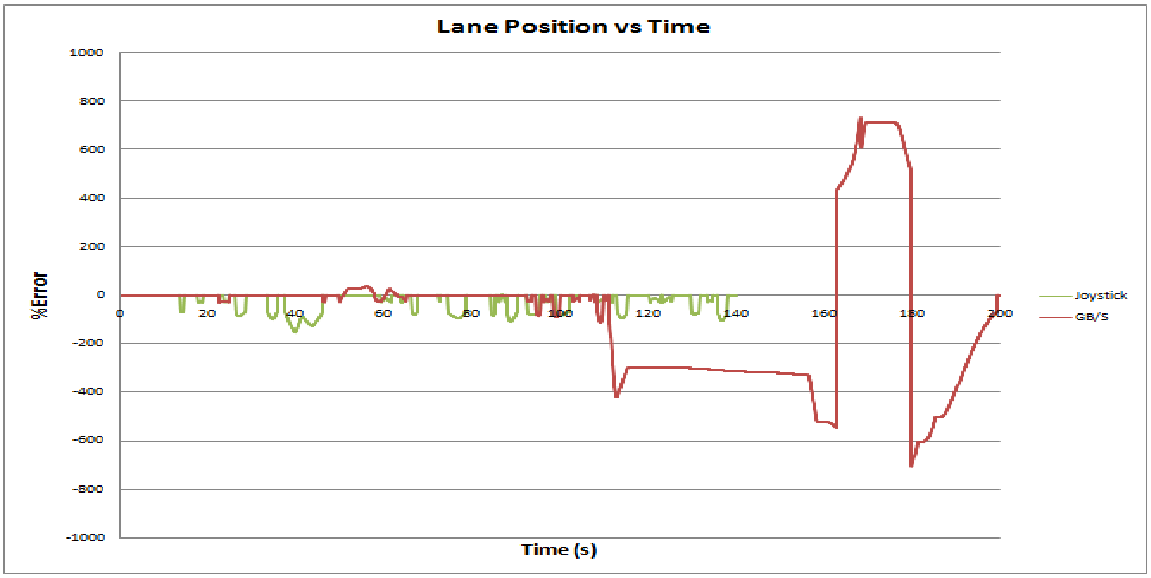


Figure C.43 - Steering Results, Participant 22

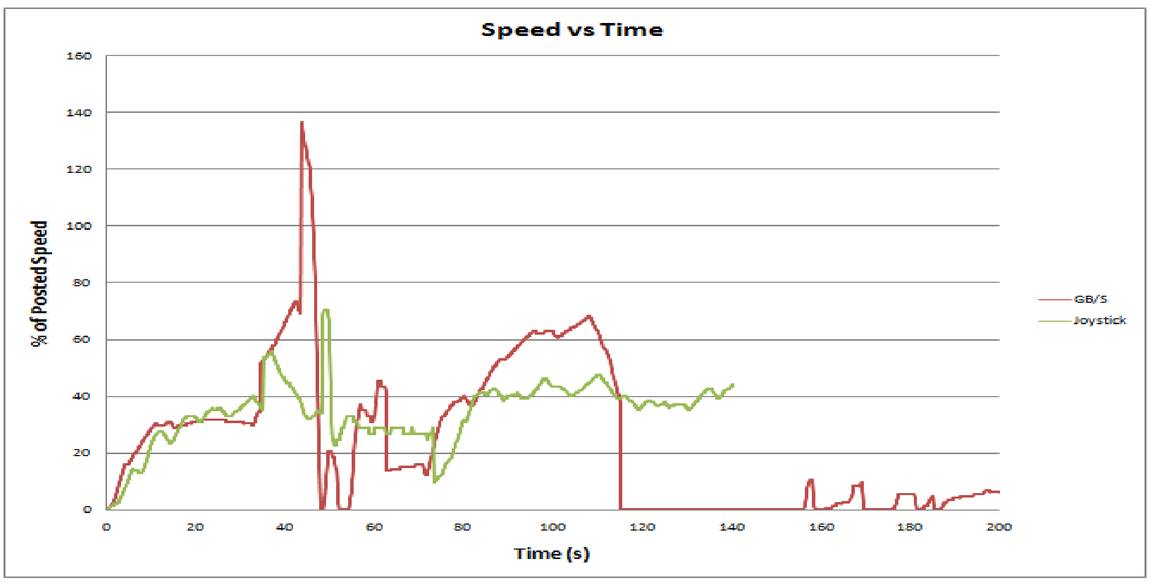


Figure C.44 – Speed Results, Participant 22

Appendix C: (Continued)

Group 3, Participant 23: (Age 49, Right-Handed, Does Use Mechanical Hand Controls)

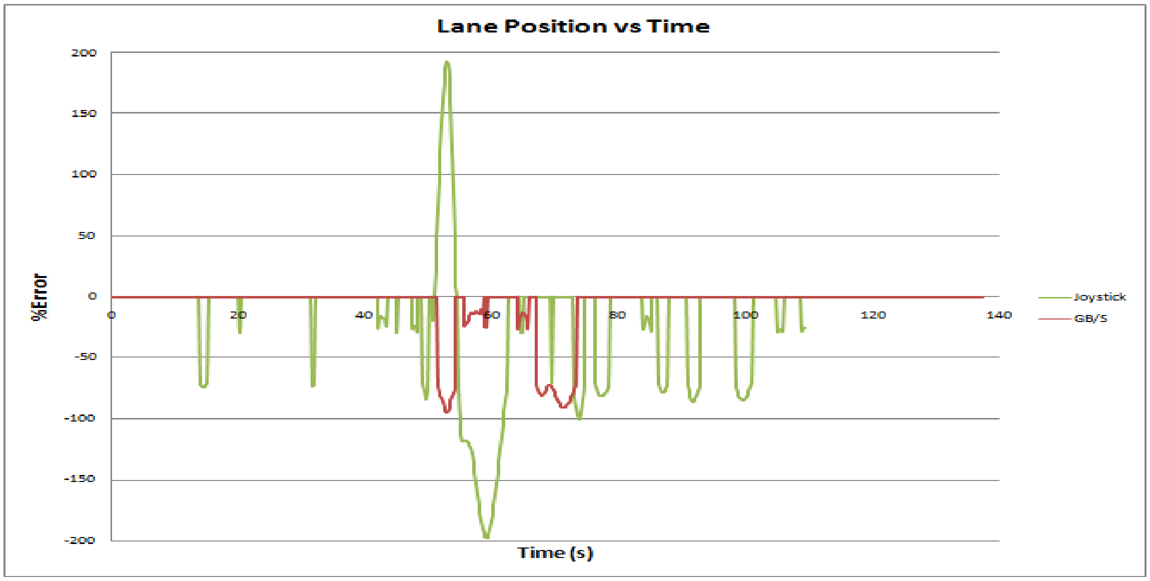


Figure C.45 - Steering Results, Participant 23

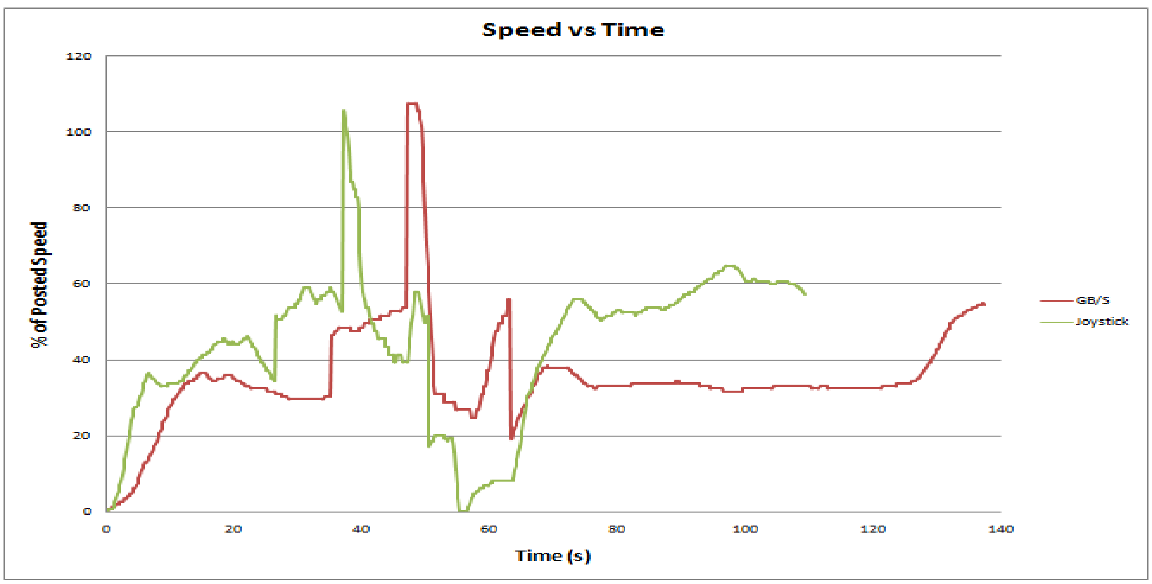


Figure C.46 – Speed Results, Participant 23

Appendix C: (Continued)

Group 3, Participant 24: (Age 45, Right-Handed, Does Use Mechanical Hand Controls)

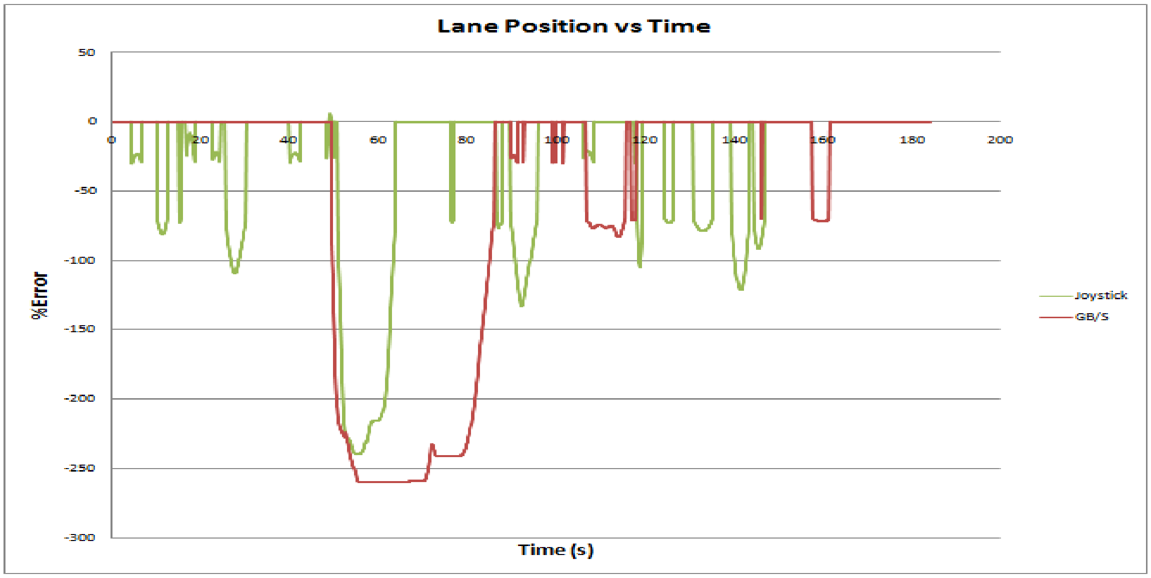


Figure C.47 - Steering Results, Participant 24

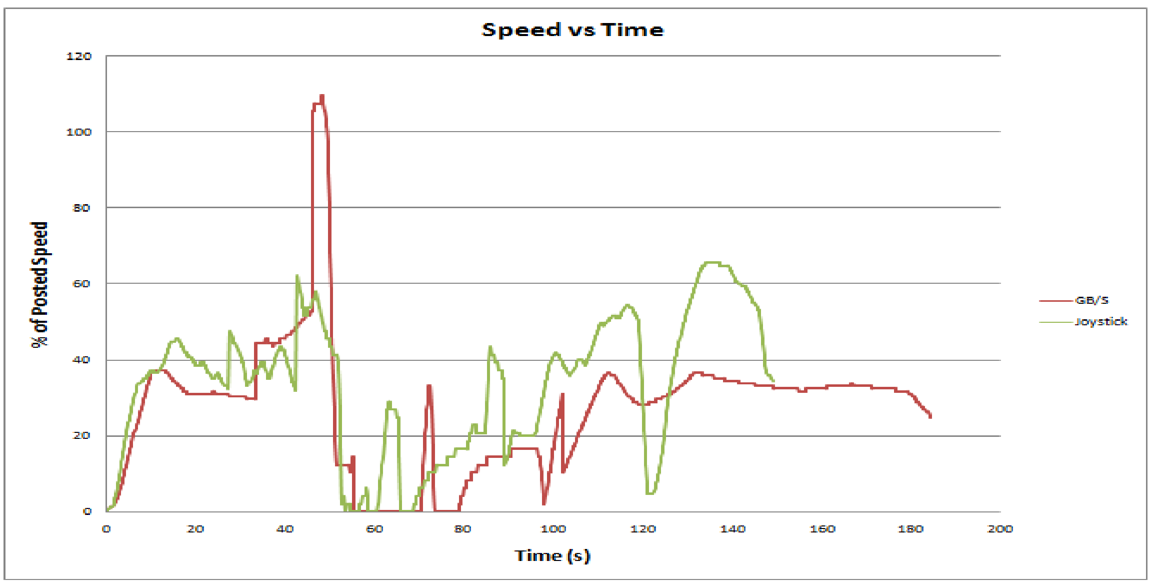


Figure C.48 – Speed Results, Participant 24

Appendix C: (Continued)

Group 3, Participant 25: (Age 48, Right-Handed, Does Use Mechanical Hand Controls)

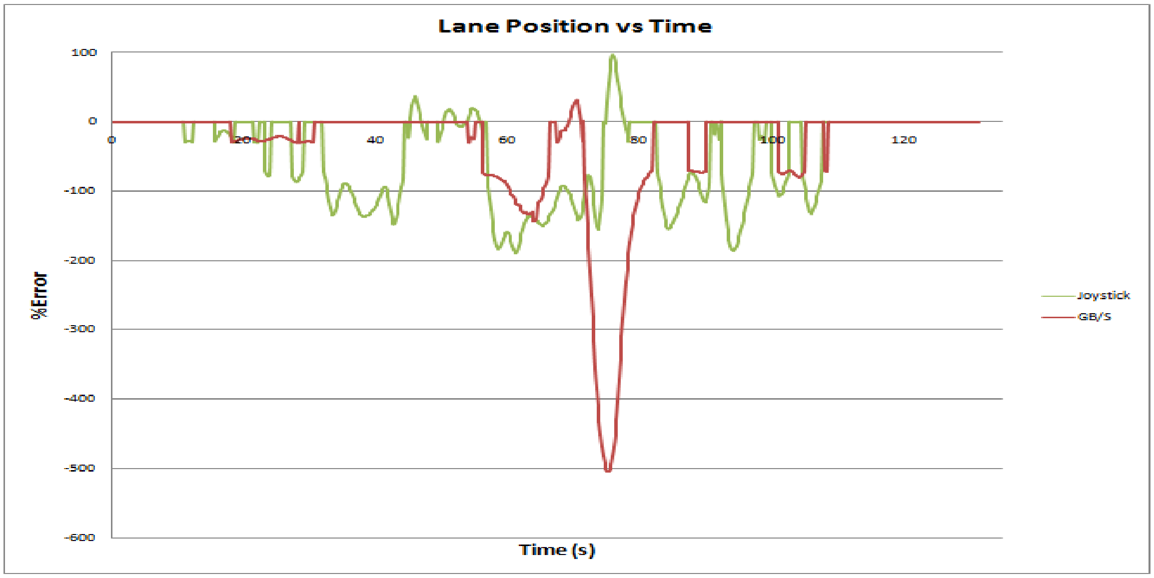


Figure C.49 - Steering Results, Participant 25

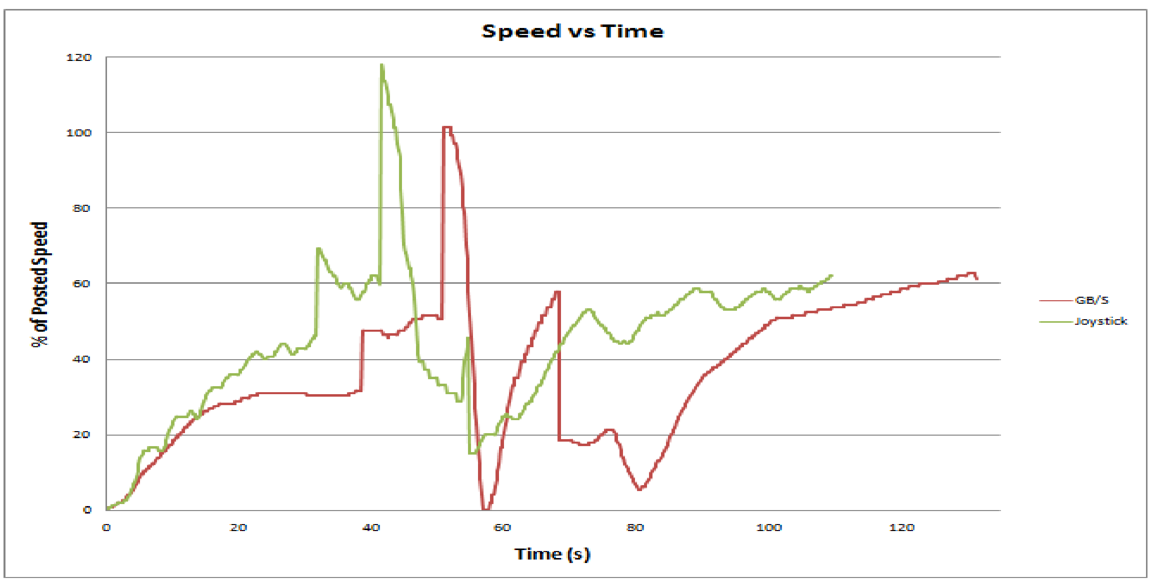


Figure C.50 – Speed Results, Participant 25

Appendix C: (Continued)

Group 3, Participant 26: (Age 26, Right-Handed, Does Use Mechanical Hand Controls)

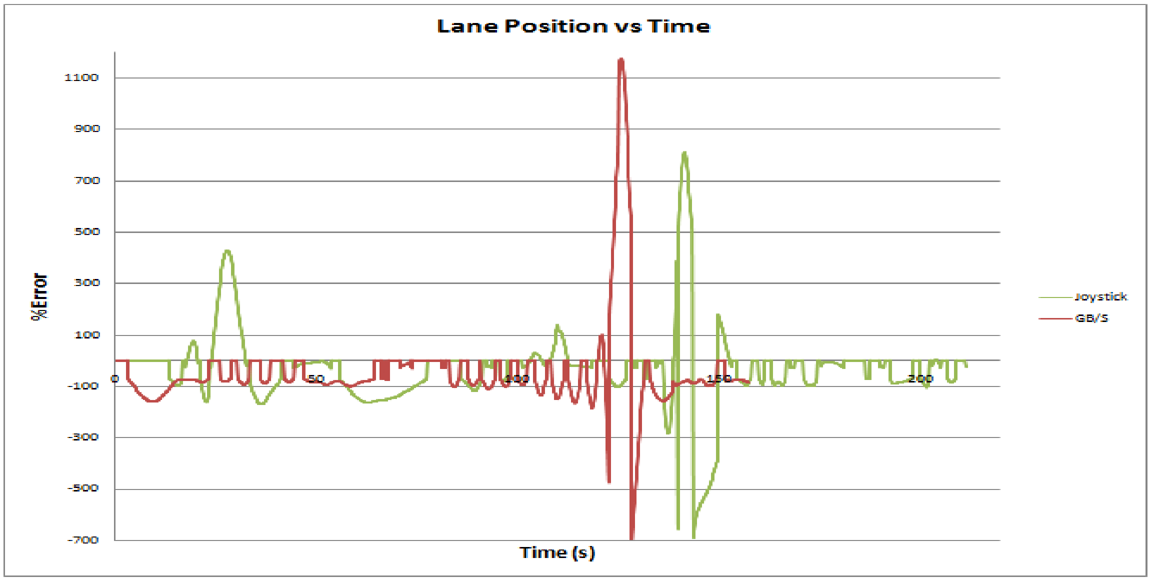


Figure C.51 - Steering Results, Participant 26

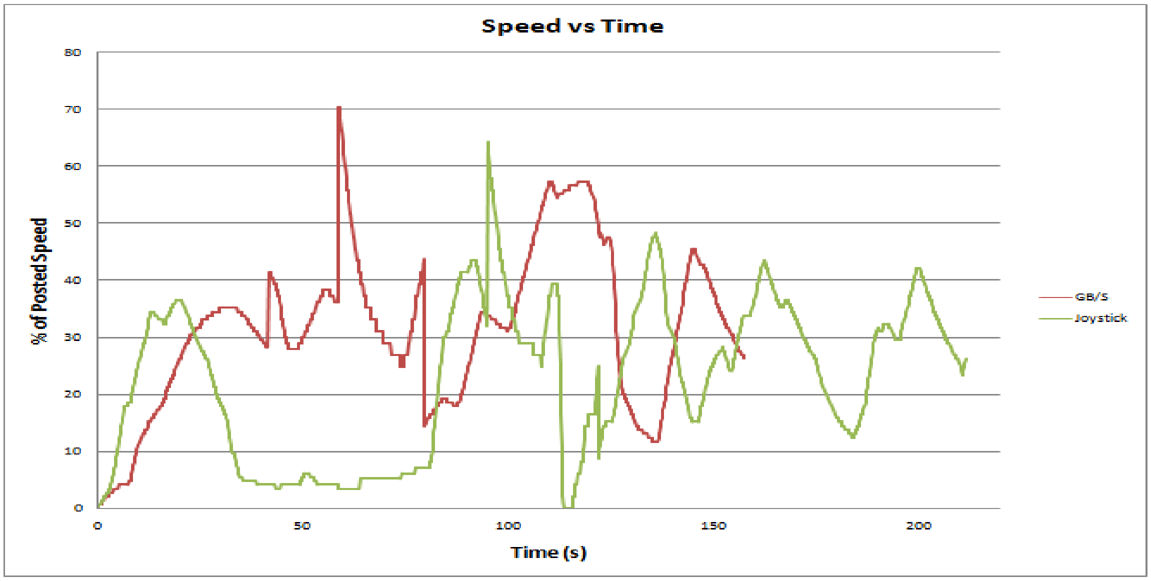


Figure C.52 – Speed Results, Participant 26

Appendix C: (Continued)

Group 3, Participant 27: (Age 27, Right-Handed, Does Use Mechanical Hand Controls)

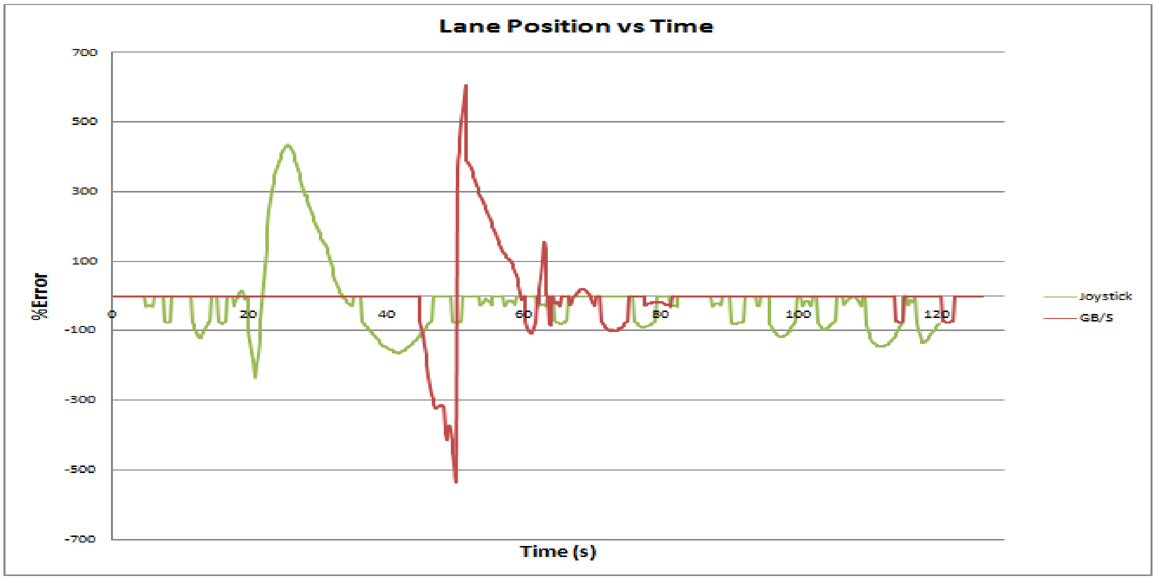


Figure C.53 - Steering Results, Participant 27

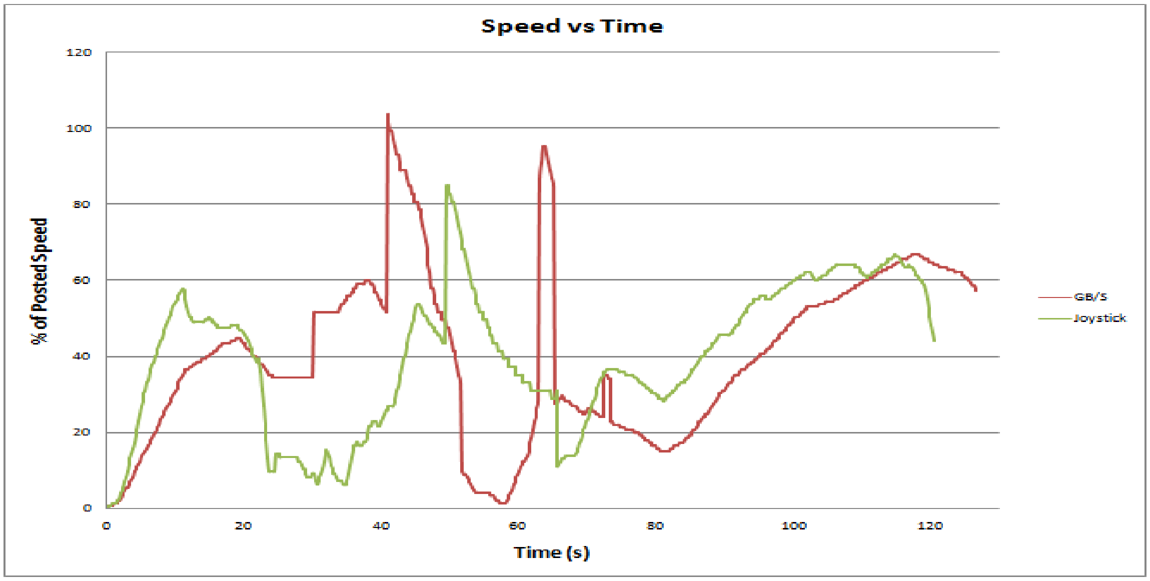


Figure C.54 – Speed Results, Participant 27

Appendix C: (Continued)

Group 3, Participant 28: (Age 55, Left-Handed, Does Use DBW Controls)

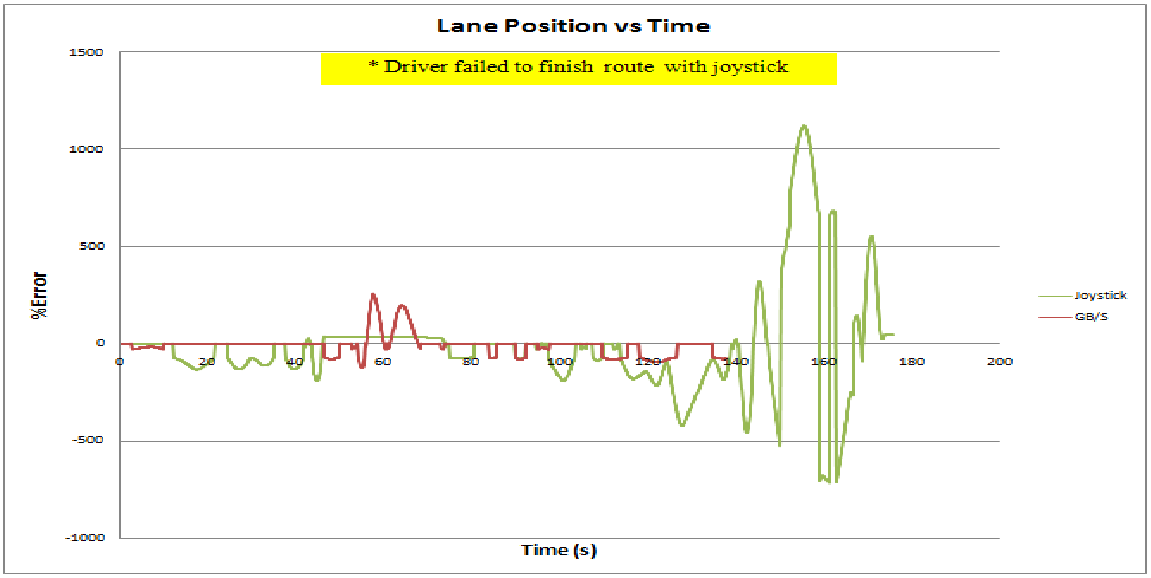


Figure C.55 - Steering Results, Participant 28

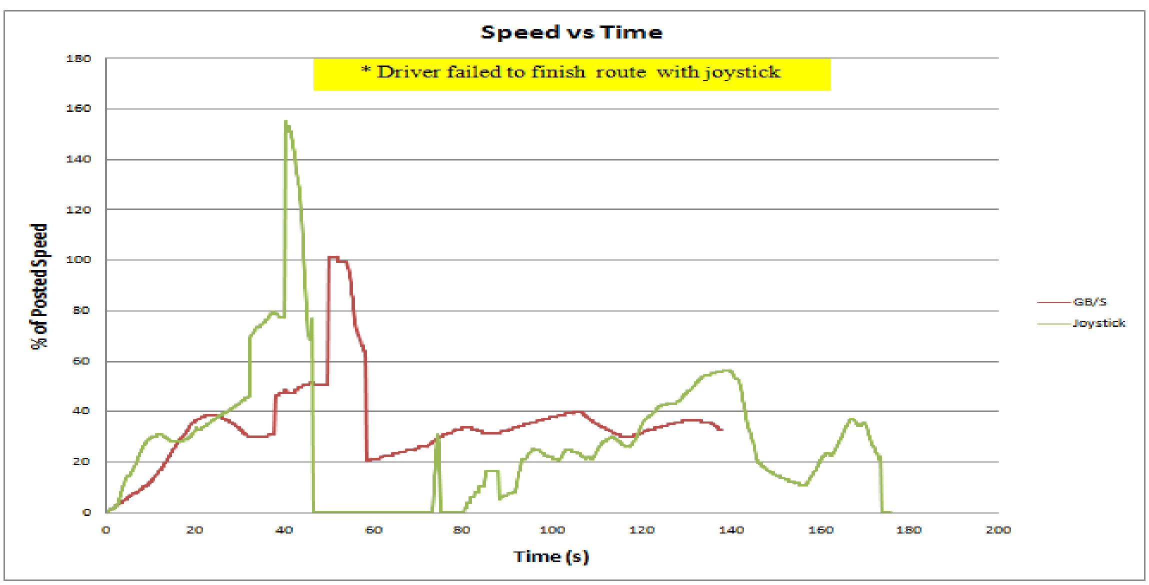


Figure C.56 – Speed Results, Participant 28

Appendix C: (Continued)

Group 3, Participant 29: (Age 40, Right-Handed, Does Use Mechanical Hand Controls)

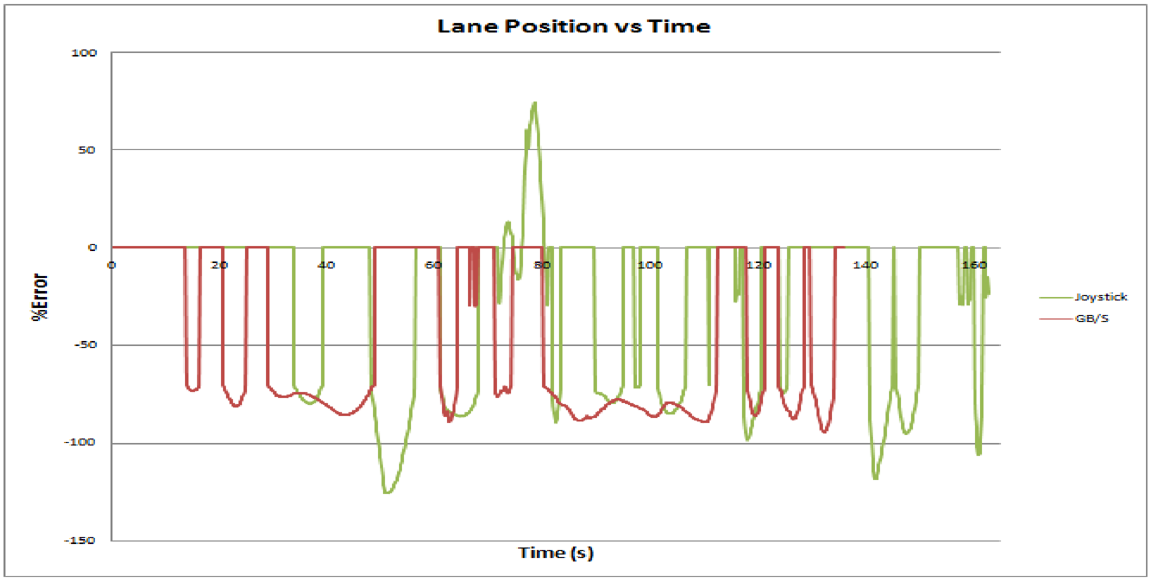


Figure C.57 - Steering Results, Participant 29

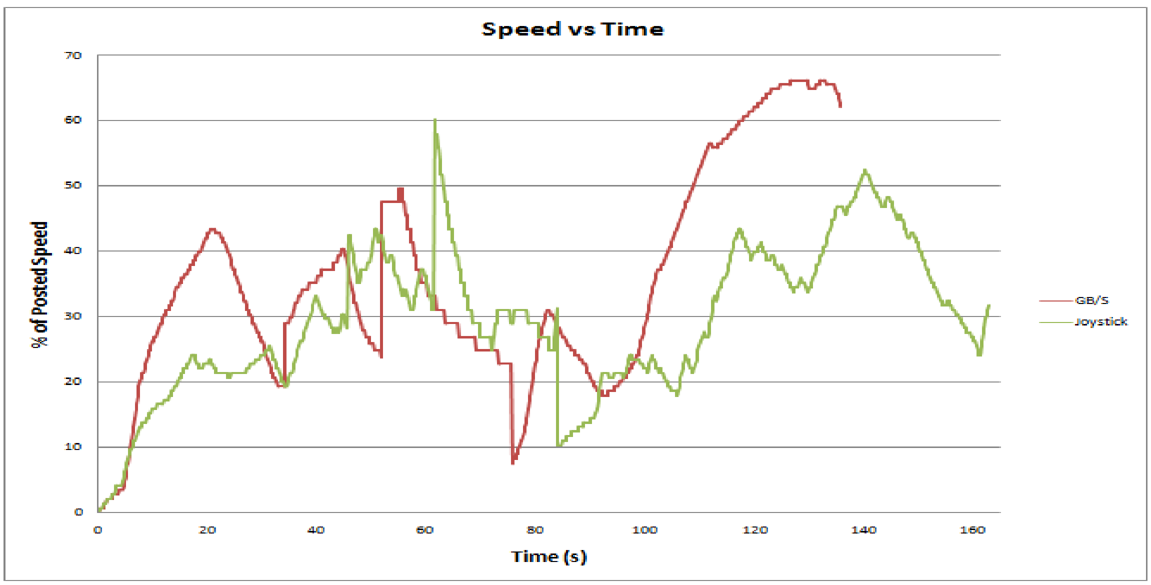


Figure C.58 – Speed Results, Participant 29

Appendix C: (Continued)

Group 3, Participant 30: (Age 34, Left-Handed, Does Use DBW Controls)

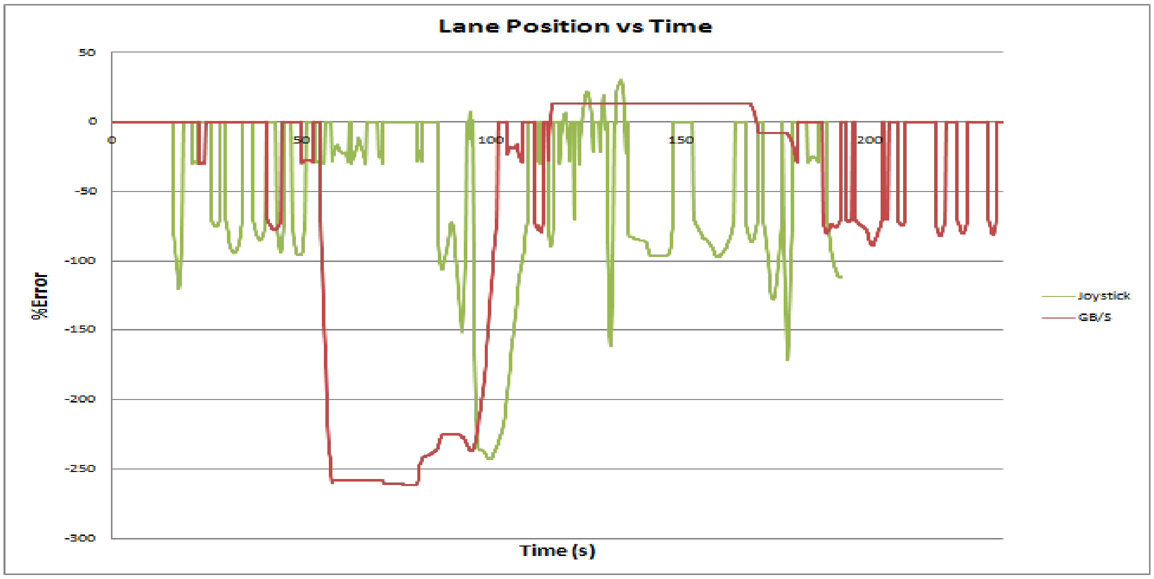


Figure C.59 - Steering Results, Participant 30

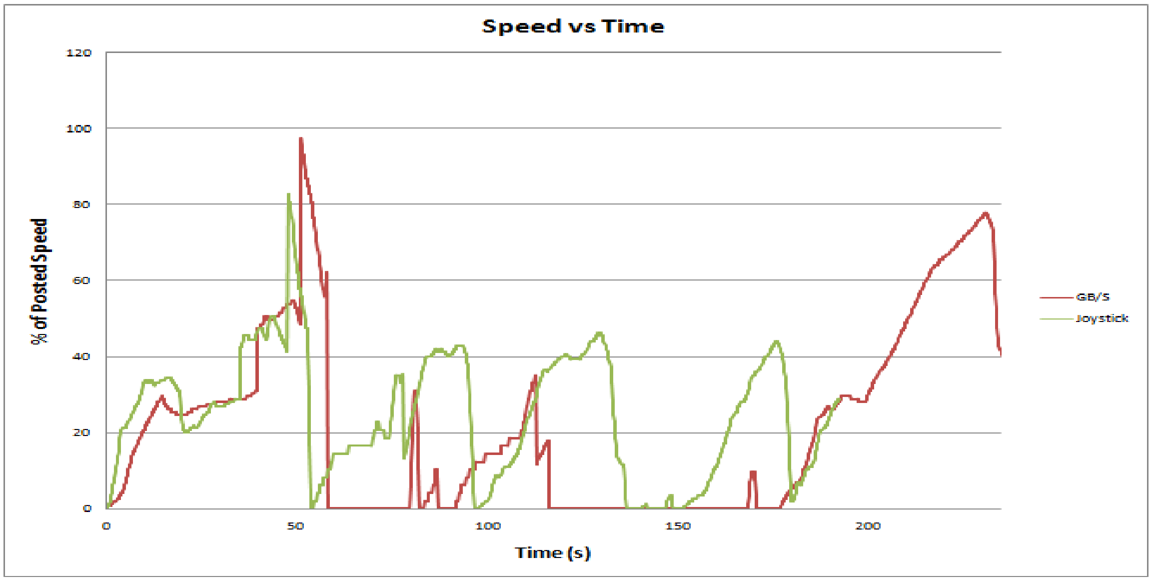


Figure C.60 – Speed Results, Participant 30

Appendix C: (Continued)

C.5. Driving in Traffic

The following chart contains the summed data for each group on all three systems for routes "A" and "E":

Table C.5 – Data for Routes "A" and "E"

A

NDBW	Time (s)	Speeding (x)	Speeding (s)	Space Cushion (x)	Space Cushion (s)	Lane Position (x)	Lane Position (s)	Missed Signal (x)	Red Light (x)
18-64	3258	11	50	6	10	120	234	80	10
65+	3176	15	56	18	27	142	269	108	4
Disability	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

E

NDBW	Time (s)	Speeding (x)	Speeding (s)	Space Cushion (x)	Space Cushion (s)	Lane Position (x)	Lane Position (s)	Missed Signal (x)	Red Light (x)
18-64	1722	0	6	5	7	97	103	21	0
65+	2038	0	0	7	13	135	194	50	0
Disability	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

A

GB/S	Time (s)	Speeding (x)	Speeding (s)	Space Cushion (x)	Space Cushion (s)	Lane Position (x)	Lane Position (s)	Missed Signal (x)	Red Light (x)
18-64	3356	1	4	2	1	121	234	90	8
65+	3893	0	0	4	8	184	525	109	6
Disability	3247	15	38	9	26	145	340	103	9

Appendix C: (Continued)

Table C.5 (Continued)

E

GB/S	Time (s)	Speeding (x)	Speeding (s)	Space Cushion (x)	Space Cushion (s)	Lane Position (x)	Lane Position (s)	Missed Signal (x)	Red Light (x)
18-64	2083	0	0	2	2	130	231	39	0
65+	2115	0	0	1	0	175	352	89	0
Disability	1679	0	0	4	4	109	183	36	0

A

Joystick	Time (s)	Speeding (x)	Speeding (s)	Space Cushion (x)	Space Cushion (s)	Lane Position (x)	Lane Position (s)	Missed Signal (x)	Red Light (x)
18-64	3153	10	29	10	23	193	455	105	5
65+	3195	6	19	10	16	226	523	165	5
Disability	3463	11	26	19	38	210	480	108	2

E

Joystick	Time (s)	Speeding (x)	Speeding (s)	Space Cushion (x)	Space Cushion (s)	Lane Position (x)	Lane Position (s)	Missed Signal (x)	Red Light (x)
18-64	2124	0	0	7	10	248	518	178	0
65+	2340	0	0	3	3	263	686	132	0
Disability	1437	0	0	7	6	186	378	90	0

Note: The columns that use *x* as the unit signify an *x* number of instances in which the error was committed.

Appendix D: Parts List and Drawings

D.1. Gear Train for Coupling Systems

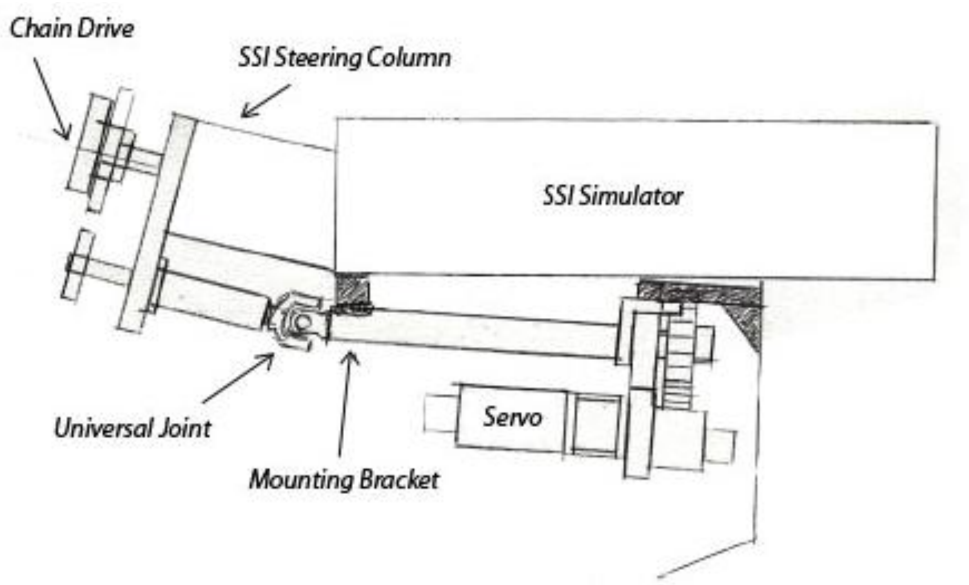


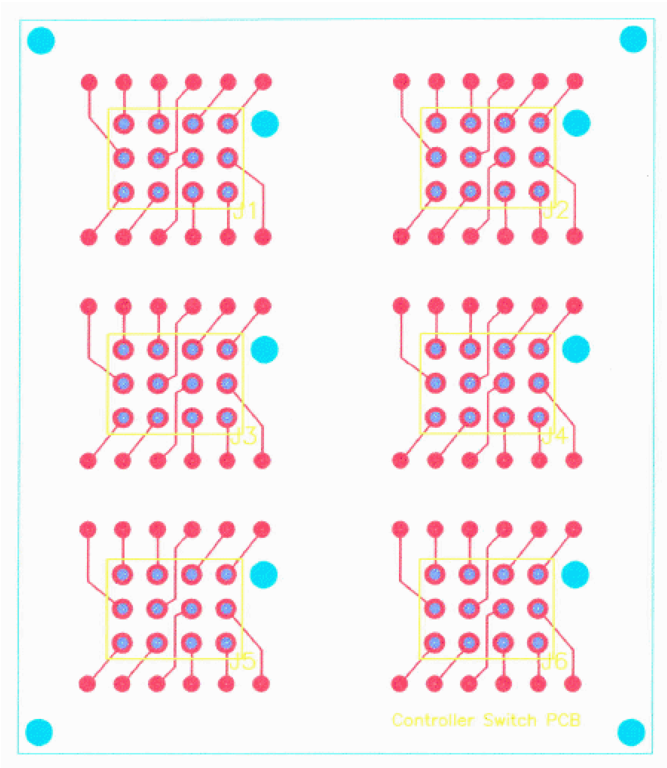
Figure D.1 - SSI/AEVIT Integration (courtesy of Matt Wills)

Table D.1 – Chain Drive Parts List

Part	Qty
#40 Sprocket, 12 teeth, 3/4" bore	1
#40 Sprocket, 16 teeth, 1" bore	1
#40 Idler sprocket ball bearing	1
#40 Roller Chain, 2'	1
#40 Roller Chain Link	1

Appendix D: (Continued)

D.2.AEVIT Controller Switch



- Red – etched copper traces
- Blue – Drilled holes
- Yellow – MATE-N-LOK plug location

Figure D.2 - Controller Switch Trace Diagram (courtesy of Matt Wills)

Table D.2 - AEVIT Parts List

Part	Qty
Tyco/AMP MATE-N-LOK socket 22-26 AWG	48
Tyco/AMP MATE-N-LOK male plug 12 pos	4
Tyco/AMP MATE-N-LOK female plug 12 pos	6
4" solid 22 AWG wire	72
Printed Circuit Board (etched according to pattern)	1
Aluminum stand-offs	4
4" x 6" x 2" Aluminum enclosure	1
2 position rotary switch	1

Appendix E: Maintenance Issues

Table E.1 - Troubleshooting

Problem	Cause
Gas/brake is disabled	Switch on the lower side of the gas/brake drive module has been disabled
Steering is disabled	Switch on the lower side of the steering drive module has been disabled
Steering servo will not rotate through its full range of motion in both directions	SSI steering wheel was not center when the steering servo was engaged
AEVIT system gives an alarm for missing coil pulse	Coil Pulse is not present, No current solution
Low Battery is indicated on the AEVIT Information Center	Battery charger has become unplugged or disconnected

Appendix F: Participant Survey

Sample Procedure Questions

Sample questions asked prior to each initial use of a control or driving aid:

1. Have you ever used this system?

If yes –

Please describe your (negative and positive) experiences with this system (specify).

   1.1. Please rank [1-5; unsafe-very safe] system safety.
   1.2. Please rank [1-5; difficult-very easy] system ease of learning to use.
   1.3. Please rank [1-5; difficult-very easy] system ease of use.
   1.4. Please rank [1-5; unreliable-very reliable] system reliability. {i.e., system behaved consistently as expected}
   1.5. How do you perceive this system?

Functional tests (acceleration, braking, steering)

Sample questions asked after each driving control system:

1. Please describe your (negative and positive) experiences with this system.
2. Was it easy to navigate/operate this system? Please describe your experience.
3. Please rank [1-5; difficult-very easy] system ease of learning to use.
4. I was able [the system allowed me] to brake on time [1-5; unable-easily able].
5. Please rank your ability to control the steering [1-5; unable-easily able].

Appendix F: (Continued)

6. I was able [the system allowed me] to accelerate to the desired speed [1-5; unable-easily able].
7. Please rank your confidence [1-5; not confident-very confident] in using this system in the beginning/at the end?
8. Please describe your experience.{i.e., confidence in driving correctly and confidence in driving safely}

Driving test routes '"A" and "E"

Sample questions asked after each test/trial using a different driving control:

1. Please describe your (negative/positive) experiences with each system.
2. Please describe your experience in learning how to use each system?
3. Please rank your ease of learning [1-5; difficult-very easy].
4. I felt that as I used the system I became more proficient (circle one):
5. Strongly disagree, Disagree; Neutral; Agree; Strongly Agree
6. Please describe your experience in navigating/operating each system?
7. Please rank your ease of operating the system [1-5; difficult-very easy].
8. Please rank [1-5; unsafe-very safe] system safety.
9. Did you feel confident using the system (specify system) at the start/end (specify)? {i.e., confidence in driving correctly and confidence in driving safely}
10. Please rank your confidence in using the system [1-5; not confident-very confident].
11. Please rank [1-5; unreliable-very reliable] the system reliability. {i.e., system behaved consistently as expected}

Appendix F: (Continued)

12. The system gave me realistic scenarios of driving (circle one):

13. Strongly disagree, Disagree; Neutral; Agree; Strongly Agree

Final questions asked after all trials

1. What system did you like most/least?
2. What system was easiest/most difficult to learn to use?
3. What system took least/most time to learn?
4. What system was easiest/most difficult to use?
5. What system was most/least reliable? {i.e., system behaved consistently as expected}
6. What system would you prefer using in your vehicle?
7. Share your ideas about equipment that would make it easier or more comfortable for you to drive?
8. How would you compare the adaptive driving equipment with conventional controls in terms of:
    - 8.1. Ease of learning to use [1-5; difficult-very easy]?
    - 8.2. Ease of use [1-5; difficult-very easy]?
    - 8.3. Reaction time (brake, accelerate, steer) [1-5; slow-very fast]
    - 8.4. Reliability [1-5; unreliable-very reliable]?
    - 8.5. Comfort [1-5; uncomfortable-very comfortable]?

If you do <u>not</u> have a disability and do <u>not</u> need an adaptive driving aid in your vehicle:

9. Would you prefer to use a DBW system over traditional means? Why/why not?

Note: The results of the survey are tabulated on the following pages.

Appendix F: (Continued)

Table F.1 - Quantitative Survey Results

Participant

BEFORE GB/S	Able-bodied 1	2	3	4	5	6	7	8	9	10	Σ	AVG	Elderly 1	2	3	4	5	6	7	8	9	10	Σ	AVG	Disabled 1	2	3	4	5	6	7	8	9	10	Σ	AVG
System Safety:																									5	5	5	5	5	5	5	4	5	4	48	4.8
Ease of Learning to Use:																									5	4	5	4	4	5	5	5	4	5	46	4.6
System Ease of Use:																									5	4	5	5	5	5	5	5	5	5	49	4.9
System Reliability:																									5	5	4	5	5	5	5	4	4	5	47	4.7

BEFORE JOYSTICK	Able-bodied 1	2	3	4	5	6	7	8	9	10	Σ	AVG	Elderly 1	2	3	4	5	6	7	8	9	10	Σ	AVG	Disabled 1	2	3	4	5	6	7	8	9	10	Σ	AVG
System Safety:																									x	x	x	x	x	x	x	x	1	x	1	1
Ease of Learning to Use:																									x	x	x	x	x	x	x	x	1	x	1	1
System Ease of Use:																									x	x	x	x	x	x	x	x	2	x	2	2
System Reliability:																									x	x	x	x	x	x	x	x	1	x	1	1

Functional Tests
Acceleration and Braking

AFTER GB/S	Able-bodied 1	2	3	4	5	6	7	8	9	10	Σ	AVG	Elderly 1	2	3	4	5	6	7	8	9	10	Σ	AVG	Disabled 1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	2	3	5	4	3	4	3	3	4	5	36	3.6	5	5	4	3	3	4	5	4	4	2	39	3.9	5	4	3	2	5	4	5	3	3	5	39	3.9
Able to Brake on Time:	3	3	5	5	4	4	3	3	2	5	37	3.7	5	5	4	3	3	3	5	3	4	4	39	3.9	4	5	4	2	5	4	5	5	1	3	38	3.8
Ability to Control Steering:	3	2	4	3	3	3	3	3	5	4	33	3.3	4	2	3	2	1	2	2	3	3	1	23	2.3	4	4	2	3	3	3	3	4	2	4	32	3.2
Able to Accelerate:	4	4	4	3	3	4	5	3	4	5	39	3.9	4	2	4	4	2	2	2	5	4	3	32	3.2	4	5	3	3	4	4	5	5	3	5	41	4.1
Confidence at Beginning:	1	3	4	2	1	2	4	3	2	3	25	2.5	3	3	3	2	1	2	3	3	3	1	24	2.4	4	2	2	2	2	3	2	1	1	2	21	2.1
Confidence at End:	3	3	5	4	3	4	3	3	4	5	37	3.7	4	4	4	5	2	3	4	4	3	2	35	3.5	5	4	3	3	4	4	4	3	1	4	35	3.5

Appendix F: (Continued)

Table F.1 – (Continued)

Able-bodied

AFTER Joystick	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	3	3	5	4	1	3	4	3	4	4	34	3.4
Able to Brake on Time:	3	4	4	4	4	4	3	2	4	4	36	3.6
Ability to Control Steering:	2	2	3	2	2	2	2	1	2	2	20	2
Able to Accelerate:	4	3	5	2	5	3	4	2	4	2	34	3.4
Confidence at Beginning:	2	2	3	3	1	2	3	2	2	2	22	2.2
Confidence at End:	3	3	4	1	3	3	3	3	4	3	30	3

Elderly

AFTER Joystick	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	3	1	2	1	2	5	1	1	2	1	19	1.9
Able to Brake on Time:	5	1	2	3	1	2	1	1	4	2	22	2.2
Ability to Control Steering:	1	1	2	2	1	2	1	2	1	1	14	1.4
Able to Accelerate:	4	1	3	4	2	3	1	3	4	2	27	2.7
Confidence at Beginning:	1	2	1	1	1	3	2	1	3	1	16	1.6
Confidence at End:	4	1	1	2	1	2	1	1	1	1	15	1.5

Disabled

AFTER Joystick	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	3	3	2	4	4	2	2	1	1	5	27	2.7
Able to Brake on Time:	4	4	5	4	5	3	4	2	1	5	37	3.7
Ability to Control Steering:	3	3	2	3	5	1	1	1	1	2	22	2.2
Able to Accelerate:	3	4	4	3	5	4	4	4	1	3	35	3.5
Confidence at Beginning:	3	2	1	2	2	1	1	1	1	1	15	1.5
Confidence at End:	4	4	1	4	5	1	2	1	1	3	26	2.6

Able-bodied

AFTER W/out DBW	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	5	4	5	4	4	4	5	4	4	5	44	4.4
Able to Brake on Time:	3	5	5	3	5	4	3	4	3	5	40	4
Ability to Control Steering:	4	3	5	4	4	3	5	4	4	5	41	4.1
Able to Accelerate:	5	5	5	3	4	4	4	4	2	5	41	4.1
Confidence at Beginning:	4	4	4	2	3	3	3	4	3	5	35	3.5
Confidence at End:	4	4	5	4	4	4	5	4	4	5	43	4.3

Elderly

AFTER W/out DBW	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	5	5	4	5	4	5	5	4	5	1	43	4.3
Able to Brake on Time:	5	4	3	5	4	4	4	2	5	4	40	4
Ability to Control Steering:	5	3	4	5	4	3	3	2	3	1	33	3.3
Able to Accelerate:	5	3	4	5	5	4	3	5	4	3	41	4.1
Confidence at Beginning:	5	4	3	3	3	2	4	4	4	1	33	3.3
Confidence at End:	5	4	4	5	4	4	4	3	4	2	39	3.9

Disabled

AFTER W/out DBW	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:												
Able to Brake on Time:												
Ability to Control Steering:												
Able to Accelerate:												
Confidence at Beginning:												
Confidence at End:												

Driving Test Routes AFTER "A" and "E"

Able-bodied

AFTER GB/S	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning:	3	3	5	4	4	4	4	4	4	4	39	3.9
Proficiency:	4	4	3	4	5	4	5	4	5	5	43	4.3
Ease of Operating System:	3	3	4	4	4	4	4	4	4	4	38	3.8

Elderly

AFTER GB/S	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning:	3	2	4	3	2	5	2	4	3	3	31	3.1
Proficiency:	4	5	4	4	2	4	5	5	5	4	42	4.2
Ease of Operating System:	4	1	3	3	2	4	1	4	3	3	28	2.8

Disabled

AFTER GB/S	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning:	5	5	5	4	4	4	5	3	5	5	45	4.5
Proficiency:	5	4	4	4	5	4	4	4	5	5	44	4.4
Ease of Operating System:	5	5	5	3	5	4	5	4	5	5	46	4.6

Appendix F: (Continued)

Table F.1 – (Continued)

System Safety	2	3	2	4	4	3	4	3	4	4	33	3.3	5	1	1	4	1	3	1	4	4	4	28	2.8	5	4	5	3	4	3	4	4	1	3	36	3.6
Confidence:	3	3	3	4	4	4	4	4	4	4	37	3.7	4	1	3	4	1	3	1	3	3	2	25	2.5	5	5	4	4	5	4	5	4	5	3	44	4.4
System Reliability:	2	5	2	5	5	4	4	4	4	4	39	3.9	5	5	4	4	2	4	5	5	3	3	40	4	5	4	5	4	5	4	5	4	1	5	42	4.2
Realism of Scenarios:	2	5	3	5	5	4	4	4	4	4	40	4	5	1	5	4	4	5	1	2	5	4	36	3.6	5	4	4	4	5	5	4	4	4	4	43	4.3

AFTER Joystick	1	2	3	4	5	6	7	8	9	10	Σ	AVG	1	2	3	4	5	6	7	8	9	10	Σ	AVG	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning:	2	2	5	2	1	3	4	3	3	2	27	2.7	3	1	4	1	1	5	1	1	1	1	19	1.9	3	3	2	3	3	2	3	2	2	5	28	2.8
Proficiency:	4	2	3	3	3	4	4	4	3	2	32	3.2	4	1	4	2	2	4	1	2	2	4	26	2.6	4	4	1	4	5	2	3	4	2	5	34	3.4
Ease of Operating System:	2	2	5	1	5	3	4	3	4	3	32	3.2	3	1	3	2	1	3	1	1	1	1	17	1.7	3	4	5	3	3	2	3	3	1	5	32	3.2
System Safety	1	2	2	4	1	3	4	1	2	2	22	2.2	4	1	4	3	1	3	1	1	1	2	21	2.1	2	4	1	3	2	1	1	3	1	4	22	2.2
Confidence:	2	2	3	2	1	3	4	2	3	2	24	2.4	4	1	4	1	1	3	1	1	1	1	18	1.8	3	4	1	4	5	2	3	3	1	3	29	2.9
System Reliability:	2	5	2	4	2	3	4	2	3	3	30	3	4	5	4	3	2	4	5	2	3	3	35	3.5	3	3	4	3	5	3	3	3	1	4	32	3.2
Realism of Scenarios:	2	5	3	4	5	4	4	4	4	4	39	3.9	4	1	3	3	4	5	1	2	5	4	32	3.2	4	4	3	4	5	4	4	4	4	4	40	4

AFTER W/out DBW	1	2	3	4	5	6	7	8	9	10	Σ	AVG	1	2	3	4	5	6	7	8	9	10	Σ	AVG	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning:	5	5	5	3	5	5	4	4	4	5	45	4.5	5	3	3	4	2	5	3	2	4	3	34	3.4												
Proficiency:	3	3	5	4	5	5	5	5	4	5	44	4.4	5	5	5	4	3	5	5	5	4	3	44	4.4												
Ease of Operating System:	5	4	5	3	5	5	4	5	4	5	45	4.5	5	2	3	4	3	5	2	4	4	3	35	3.5												
System Safety	3	2	5	4	5	4	5	5	4	5	42	4.2	5	1	3	4	2	5	1	4	5	2	32	3.2												
Confidence:	4	4	5	3	5	4	5	5	5	5	45	4.5	5	1	3	4	3	5	1	3	4	2	31	3.1												
System Reliability:	3	5	4	4	5	4	5	5	4	4	43	4.3	5	5	3	5	3	5	5	2	3	2	38	3.8												

Appendix F: (Continued)

Table F.1 – (Continued)

Realism of Scenarios:	2	5	2	4	5	4	5	4	3	4	38	3.8	5	2	4	4	4	5	2	2	4	4	36	3.6												

Comparison of controls	Able-bodied												Elderly												Disabled											
DBW vs Conventional	1	2	3	4	5	6	7	8	9	10	Σ	AVG	1	2	3	4	5	6	7	8	9	10	Σ	AVG	1	2	3	4	5	6	7	8	9	10	Σ	AVG
Ease of Learning to Use:	2	2	5	4	3	3	4	4	4	4	35	3.5	4	1	3	2	2	5	1	2	4	2	26	2.6												
Ease of Use:	2	2	2	4	4	4	3	2	3	4	30	3	4	2	1	2	2	2	2	1	3	1	20	2												
Reaction Time to Brake:	3	4	4	4	5	4	3	4	2	3	36	3.6	4	2	3	4	3	2	2	3	3	3	29	2.9												
Reaction Time to Accelerate:	3	4	5	4	3	4	3	4	3	3	36	3.6	4	5	3	4	2	3	5	4	3	5	38	3.8												
Reaction Time for Steering:	2	3	1	3	3	3	3	2	3	4	27	2.7	4	5	3	3	1	2	5	4	2	5	34	3.4												
Reliability:	2	5	2	4	3	3	4	2	3	3	31	3.1	5	5	3	4	2	2	5	4	3	3	36	3.6												
Comfort:	2	4	4	4	5	4	4	4	4	3	38	3.8	5	1	4	3	2	2	1	3	4	4	29	2.9												