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# The Development of an Adaptive Driving Simulator

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# The Development of an Adaptive Driving Simulator

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering
College of Engineering
University of South Florida

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Virtual reality, spinal cord injury, rehabilitation, drive-by-wire, motion cueing

# DEDICATION

I dedicate this thesis to my parents, Lisa and Bill, my sister Emily and my boyfriend, Marvin.

# ACKNOWLEDGMENTS

I would like to acknowledge the National Science Foundation grant funding the CAREN system. I thank my committee members Stephanie Carey, Rajiv Dubey and Kyle Reed for supporting and guiding me through my years here at the University of South Florida. I would also like to thank everyone from the Rehabilitation and Prosthesis Testbed (RRT) for their help with this study, especially Adrian Johnson for helping me with the electronics and Kaitlin Lostroscio and Nick Alfrey for helping me with the table assembly. In addition, I would like to thank my family and friends for their love and support.

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## ABSTRACT

The ability to drive a car is an important skill for individuals with a spinal cord injury to maintain a high quality of life, particularly their freedom and independence. However, driving with a physical disability often requires the installation of an adaptive driving system to control steering, gas, and braking. The two main types of adaptive driving controls are mechanical and electrical, also known as drive by wire (DBW). DBW controls work by converting electric signals to mechanical actuators. Driving simulators are useful tools for adaptive driving systems because they allow users to test different control devices, to practice driving without the dangers of being on the road, and can be used as a safe way to evaluate disabled drivers. This study focused on the development of a dynamic driving simulator using DBW controls because many studies focus on mechanical controls and not DBW controls and often use static simulators.

The simulator was developed using the Computer Assisted Rehabilitation Environment (CAREN) virtual reality system. The CAREN system (Motek Medical, Amsterdam, Netherlands) includes a six degree of freedom (DOF) motion base, an optical motion capture system, a sound system, and a 180-degree projection screen. The two DBW controls, a lever device to control the gas and brake and a small wheel device to control steering, sent an electric signal to a Phidget microcontroller board, which interfaced with the CAREN system. Several different driving scenarios were created and imported into CAREN's D-Flow software. A program was developed in D-Flow to control the scene and motion of the platform appropriately based on the DBW controls via the Phidget. The CAREN system dynamically controlled the motion platform based on the user's input. For example, if the user applied the brake suddenly, the user felt a deceleration from the motion platform moving backwards. Human testing was performed and through the use of a survey, feedback about the system was obtained. Changes were made to the simulator using the feedback obtained and further testing showed that those changes improved the simulator. The driving simulator showed the capability to provide dynamic feedback and, therefore, may be more realistic and beneficial than current static adaptive driving simulators. The dynamic adaptive driving simulator developed may improve driving training and performance of persons with spinal cord injuries. Future work will include more human testing. The dynamic feedback provided through the system's moving platform and virtual camera movement will be optimized in order to perform similarly to a real car. Testing will also be completed with and without the dynamics from the moving platform to see how this type of feedback affects the user's driving ability in the virtual environment.

# [1]CHAPTER 1: INTRODUCTION

## 1.1 Motivation

When individuals with disabilities start to learn how to drive with adaptive driving equipment, the majority of the training is completed on the road. This can be dangerous for the driver, trainers, and others who are on the road at the same time. The user may not be able to operate the adaptive driving equipment properly because of inexperience and difficulties with the dynamics of being on the road. Persons with spinal cord injury may especially have difficulties with torso control. Driving simulators are useful tools for a wide variety of disabilities because they allow users to practice driving without the dangers of being on the road. In addition to spinal cord injury, simulators have been used for numerous disabilities such as dementia [1], epilepsy [2], traumatic brain injury [3], and chronic whiplash associated disorders [4].

Driving simulators can either be static or dynamic. Static driving simulators are stationary and only provide visual feedback while dynamic driving simulators provide both visual and dynamic feedback that improves the realism of being on the road. The two types of adaptive driving controls are mechanical and drive-by-wire (DBW). Mechanical controls mechanically attach to the steering wheel and gas and brake pedals and are used with people that have good torso control. DBW controls work by converting electric signals to mechanical actuators and are used with people that have very limited mobility.

Most studies use static driving simulators and mechanical adaptive driving controls. For this reason, this study aimed to develop a dynamic driving simulator using DBW controls. Creating

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[1] Portions of Chapters 1 through 4 were published in ASME IMECE [37]. Permission is included in Appendix A.

dynamic feedback will increase the realism both for the driver’s benefit and the trainer’s benefit because having dynamic feedback will affect how a person drives. A benefit of having controlled dynamic feedback is that it can be gradually increased to allow the driver to adjust. Using DBW controls will benefit those who have spinal cord injuries that severely limit their mobility. Learning how to drive will greatly increase the quality of life and independence for those people.

## 1.2 Thesis Outline

This thesis is split into eight chapters. This first chapter introduced and provided motivation behind the thesis. The second chapter provides background information on driving simulators and adaptive controls. The third chapter introduces the hardware used. The fourth chapter goes through the theory involved and the fifth chapter shows how the software was programmed. The sixth chapter discusses testing methods. The seventh chapter shows the results of testing and discusses the results. Finally, the eighth chapter draws conclusions from the results.

# CHAPTER 2: BACKGROUND

## 2.1 Spinal Cord Injury

According to The National Spinal Cord Injury Statistical Center there are approximately 12,500 new spinal cord injury (SCI) cases each year [5]. As of 2014, there are about 276,000 people living with SCI in the United States. Since 2010, motor vehicle crashes are the leading cause of SCI followed by falls. Figure 1 shows causes of SCI broken down by percentage.

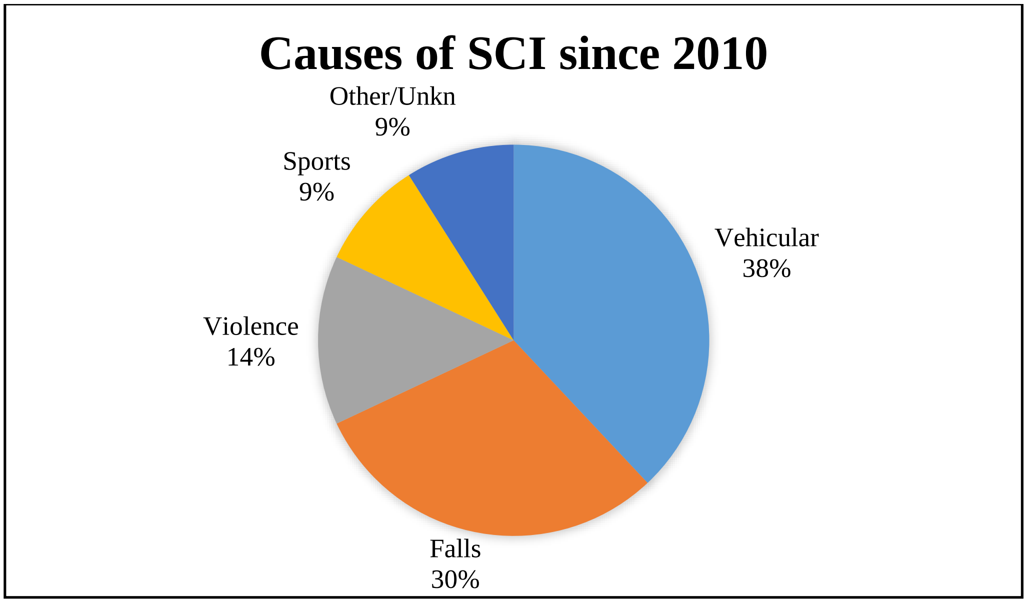

Figure 1 Causes of SCI since 2010 [5]

Tetraplegia, or quadriplegia, is caused from injury to the brain or cervical region of the spinal cord. It results in the full or partial paralysis of all four limbs and torso. Paraplegia is caused from injury to the brain or to the spinal cord in the thoracic, lumbar, or sacral region. It results in full or partial paralysis of the lower extremities [6]. Figure 2 shows these regions of the spinal cord. The cervical region consist of seven vertebrae (C1 through C7), the thoracic consists of 12 vertebrae (T1 through T12), the lumbar region consists of 5 vertebrae (L1 through L5), and the sacral region consists of 5 vertebrae that are fused together (S1 through S5). Below the sacrum is the coccygeal region, or the tailbone. The most common type of SCI is incomplete tetraplegia resulting in 45% of cases followed by incomplete paraplegia (21%), complete paraplegia (20%), and complete tetraplegia (14%) [5].

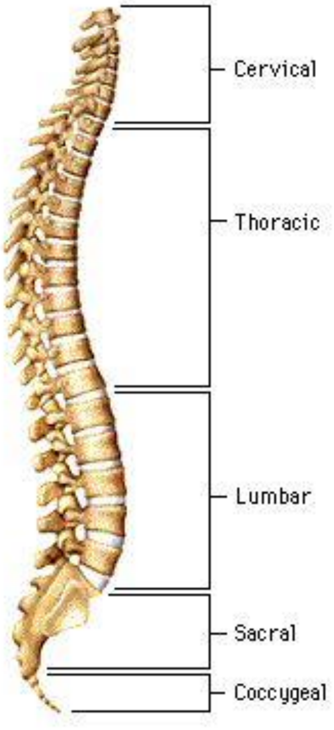

Figure 2 Regions of the Spinal Cord [6]

Being able to drive contributes to an independent lifestyle. Mobility is important for employment, social activities, and general daily living. Vehicles must be adapted for persons with SCI to give them the same amount of driving ability as a non-disabled driver. This is done through reduced effort steering devices and adaptive gas and brake controls. Once a vehicle is adapted for a disabled driver, the driver must be evaluated to make sure they are able to drive independently. Evaluation tests include checking for control of the vehicle, maneuverability, speed, stability, traffic violations, and fatigue.

## 2.2 Adaptive Controls

As mentioned earlier, vehicles must be adapted for persons with SCI to give them the same amount of driving ability as a non-disabled driver. Adaptive controls are instruments that aid in the functions of steering, accelerating, and braking. The type of adaptive controls to be used depends of the level of injury and function of the individual. Mechanical adaptive controls are relatively cheap, simple, and are generally used for paraplegia injuries while drive-by-wire adaptive controls are more expensive, complex, and are used with tetraplegia injuries.

### 2.2.1 Mechanical Adaptive Controls

Mechanical adaptive controls are for people that still have upper mobility. There are no electronics involved in these systems. Mechanical hand controls mechanically attach to the gas and brake to allow hand control. These controls do not get in the way of able bodied drivers. Four basic types of hand controls are push/pull, push/right angle, push/twist, and push/rock [7]. Push/pull controls require the driver to push forward to brake and pull backwards to accelerate, or vice versa. Push/right angle requires the driver to push forward to brake and pull down towards the lap to accelerate. Push/twist requires a twisting motion to accelerate and pushing to brake. Push/rock requires to rock back to accelerate and forward to brake. Other forms of mechanical controls include steering knobs and steering grips. These steering aids mechanically attach to the steering wheel to make it easier to turn the wheel.

### 2.2.2 Drive-by-Wire Adaptive Controls

Drive-by-Wire (DBW) technology is used in cars to control steering, acceleration, and braking. Before DBW, a physical connection existed between the driver and control of the vehicle. For example, when a driver pushes on the gas pedal in a traditional throttle control vehicle, a cable pulls the throttle open. In using DBW, no such physical connection exists. When the gas pedal is pressed, an electrical signal is sent to an actuator that opens the throttle. DBW works by converting electrical signals from the driver's input devices to mechanical actuators that control a car's steering, acceleration, and braking [9]. With DBW adaptive controls, the input devices used are called the primary controls. The three types of primary controls are lever, wheel, and joystick. Lever devices control the gas/brake functions while the wheel devices control the steering function. Joystick devices move along two axes so they can control both the steering and gas/brake functions. Some of these input devices from Electronic Mobility Controls (EMC©) that will be used in this study can be seen in Figure 3. Some primary controls also provide force feedback to the user [38]. DBW secondary controls include all other driving functions besides steering, gas, and brake such as windshield wipers, horn, and lights. These functions can be controlled on a touch screen display.

Figure 3 Drive-By-Wire Primary Controls. Left-Gas/Brake Lever. Right-Reduced Effort Steering Wheel

### 2.3 Driving Simulators

Driving simulators can be effective rehabilitation and training tools. They can be used to train individuals to learn how to drive with a disability in a safe and controlled environment before driving on real roads, which can be dangerous for an inexperienced driver. Two types of driving simulators are static and dynamic. Dynamic driving simulators have dynamic feedback whereas static driving simulators do not.

### 2.3.1 Static Driving Simulators

Static driving simulators use either a projection screen or a computer screen for visual feedback and do not use any sort of dynamic feedback. This makes them much simpler and more common than dynamic driving simulators. Static driving simulators can be played as a video game on a PC and driven using a gaming steering wheel. Static driving simulators are also used in researching driving behaviors. Researchers in Korea developed a driving simulator for rehabilitation that used a real car designed for the handicapped using mechanical adaptive controls. A beam projector and screen were used to display the virtual environment [11, 12]. This simulator can be seen in Figure 4.

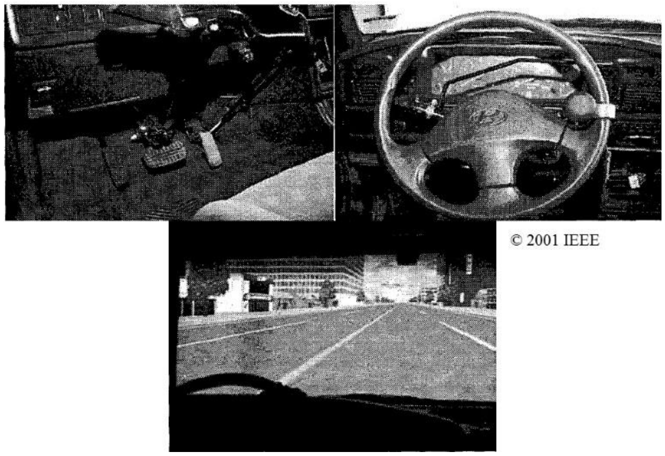

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Figure 4 Static Driving Simulator that Uses Mechanical Hand Controls [11]

Boyce et al. used a computer simulator, shown in Figure 5, to study the difference between two types of hand controls and found that there was no significant difference expect for preference based on previous experience [13]. Carlozzi et al. studied the difference between a three screen display and a head mounted display and found that either one would be a suitable option for use in a driving simulator [14]. These visual feedback driving simulators lack realism, though, because they do not provide any sort of dynamic feedback.

Figure 5 Hand Control Study Experimental Set-Up [13]

### 2.3.2 Dynamic Driving Simulators

More advanced simulators have started to use dynamic feedback to improve the simulator experience. These simulators use a platform that moves using actuators. These can be used for testing new vehicle features such as collision warning systems [15] and for researching driving behaviors such as the role of lateral acceleration in curve driving [16].

The motion platform of dynamic driving simulators needs to simulate acceleration felt while driving while still maintaining its workspace. Techniques involve optimizing the acceleration produced to the amount of workspace available. The process of simulating larger motions with smaller motions in order to appear real to the user is called motion cueing. There are four main types of motion cueing algorithms and they are the classical, adaptive, optimal, and predictive algorithms. The most common is the classical algorithm and is what will be used in this study as a starting point since it is easiest to implement.

*The classical algorithm* uses high pass filters to render high frequency motion as initial motion cues. The filtered motion is translated to platform longitudinal motion, lateral motion, and yaw angles. By choosing the correct filter parameters by looking at a “worst case” scenario involving the highest accelerations possible, the platform workspace can be maintained. The classical algorithm also uses low pass filters to render low frequency motion as sustained motion cues. These sustained cues are translated to tilt and roll angles through what is called tilt coordination, and will be discussed later. The classical algorithm was first introduced by Schmidt and Conrad in 1970 [17] for use in a flight simulator and developed in more detail by Reid and Nahom in 1985 [18].

The classical algorithm is simple and easy to implement although has two major flaws. One disadvantage is that there can be strong false cues, motion cues that do not mimic reality, because of the high pass filtering effects. These can cause motion sickness. Another disadvantage is that the full workspace is not optimally used because the filter parameters are set for the worst case scenario. These have been discussed by Fang [19] and Reymond [20]. Other algorithms have been produced in order to create better motion cueing, but are more complex than the classical algorithm.

*The adaptive algorithm* was developed by Parrish et al. in 1975 [21] and is similar to the classical algorithm but the parameters are variable and are calculated at each time step. A cost function is minimized which includes the acceleration error and workspace boundaries. The number of false cues is reduced this way.

*The optimal algorithm* was developed by Sivan in 1982 [22] and uses a model of the vestibular system to reduce the human perception error between reality and the simulator.

*The predictive algorithm*, introduced by Dagdelen [23] in 2004, uses the concept of model predictive control (MPC). It predicts future events in order to optimize the signals.

There have been many advanced dynamic driving simulators created since the 1970’s, summarized by Slob [24]. Slob’s literature survey explains that high level driving simulators have at least 6 DOF through the use of a hexapod motion platform. Fixed base systems are fixed to one location while moving base systems are attached to a XY table.

One high level driving simulator that Slob lists is the Renault driving simulator. One Renault driving simulator uses a car placed on a 6 DOF fixed motion platform, shown in Figure 6. Force feedback is felt on the steering wheel, brake, clutch, and accelerator [20, 25]. This particular Renault driving simulator is placed on a fixed motion base while a more recent Renault driving simulator, named ULTIMATE, consists of a 6DOF hexapod placed on a XY table, creating a moving base system. The ULTIMATE driving simulator is used for applications such as driver assistance systems [26]. The ULTIMATE driving simulator is shown in Figure 7.

Figure 6 Fixed Base Renault Driving Simulator [25]

Figure 7 Moving Base ULTIMATE Driving Simulator [26]

Some advanced driving simulators have been used for spinal cord injury. One study showed that using virtual reality and dynamic feedback can significantly improve driving ability following spinal cord injury [27]. The same study, which used a single axis tilting platform, found that improvements were not as significant in uphill and downhill driving because the tilting required more posture and balance. Balance and posture are factors that are not considered in non-moving simulators. Another study used a moving base system to assess the driving ability of drivers with tetraplegia and found that spinal cord patients performed tasks equally as well as able-bodied drivers but had a slightly longer reaction time [28]. The SCI patients also showed more fatigue from braking and accelerating.

## 2.4 Previous Work

Researchers at the University of South Florida (USF) have developed a drive-by-wire driving simulator using Advanced Electronic Vehicle Interface Technology (AEVIT) DBW controls and a static driving simulator from Simulator Systems [29]. This system worked by connecting the AEVIT servo motors to the steering column and brake pedals of the simulator. This system was placed into a cut away van, which was wheelchair accessible. It was also able to accommodate those not in a wheelchair. The driver had three options for controlling the simulator.

Two were with DBW controls, a 4-way joystick and a reduced effort steering wheel/gas-brake lever combination.  The third option was using standard driving controls. This system can be seen in Figure 8. Previous studies using this system showed that the steering wheel/gas-brake lever combination was easier to learn and to operate than the joystick system [30]. The USF system lacked realism in that the screens were small, there was no peripheral vision, and there was no dynamic feedback. This thesis addressed these issues by creating a new driving simulator system that uses a 180 degree projection screen and motion platform.

Figure 8 Previous Driving Simulator at USF [29]

# CHAPTER 3: HARDWARE

## 3.1 CAREN

The Computer Assisted Rehabilitation Environment (CAREN) system, shown in Figure 9, is a state of the art virtual reality system used for rehabilitation purposes. The system was developed by Motek Medical [31] and USF installed a CAREN system in November 2013.

Motek Medical integrated the following components in the CAREN system:

- 6 DOF motion base
- Dual belt treadmill
- 12 camera motion capture system
- 180 degree projection screen
- Surround sound system
- Safety Harness
- D-Flow programming software

One benefit of using the CAREN virtual reality system for a DBW driving simulator is that it gives the user a 180 degree view that is not possible with separate screen displays. This allows drivers to feel more integrated into the virtual world. Another benefit is the CAREN system's moving and rotating platform, which can be programmed to move in accordance to the user's input. This simulator, which mimics the dynamics of being on the road, is beneficial to persons with spinal cord injury because the user has to incorporate torso balance and control. An additional benefit is the system's D-Flow software. It allows these multiple components to be combined into one real-time device. The user's actions are defined as input and the various CAREN components are defined as outputs. Applications can be programmed that control how the CAREN components react to the user's inputs.

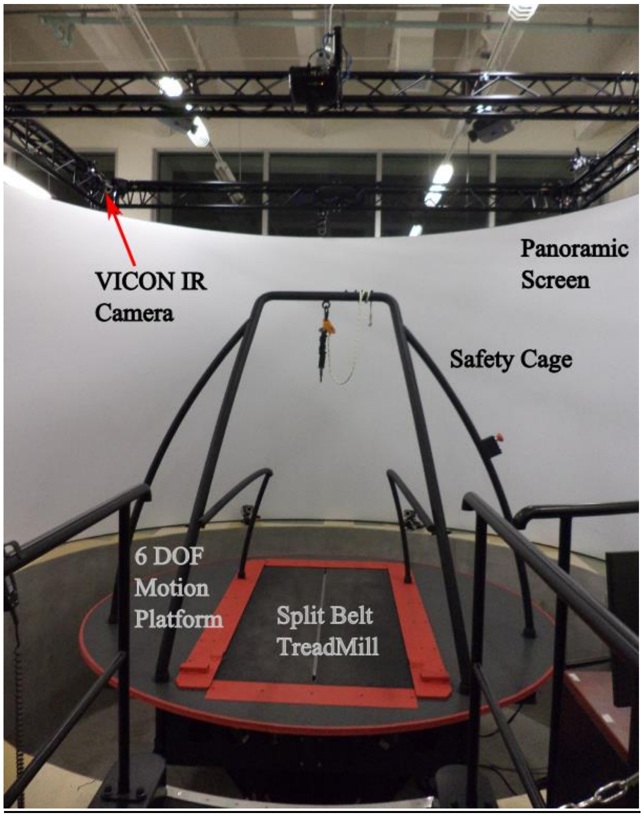


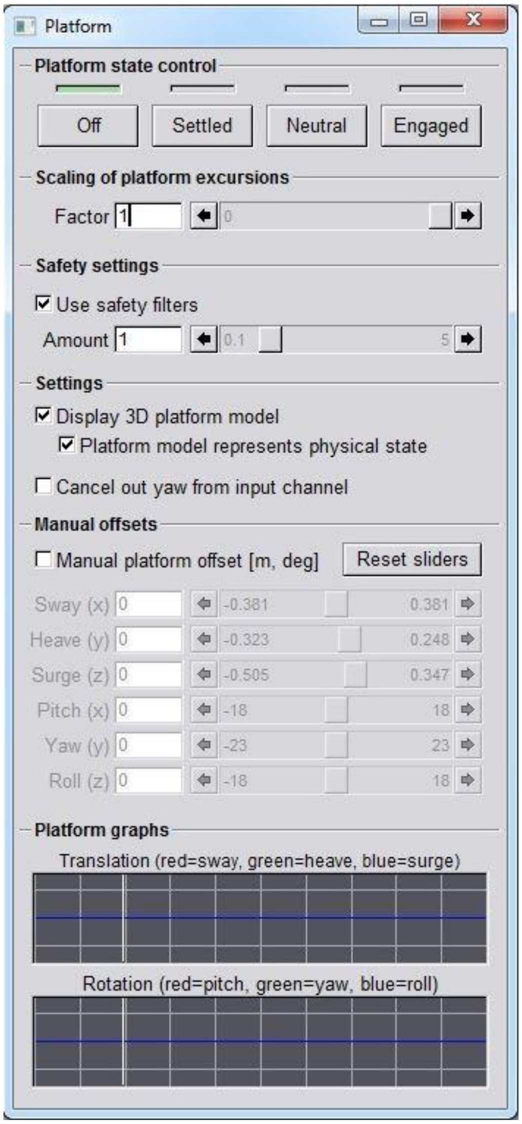
Figure 9 CAREN System at USF

### 3.1.1 Projection Screen

Three F22 projectors from Barco (Belgium) display images on the 180 degree panoramic screen. Each image is split into three sections. These sections are projected in such way that they overlap, creating a sense of continuity. This sense of continuity is called blending.

### 3.1.2 6 DOF Motion Base

The 6 DOF motion base translates in three directions and rotates about 3 axes. It has a 1000 kilogram payload and a 3 meter diameter. The scaling of platform excursions can be altered that limit the amount of movement it performs. Second order Butterworth safety filters can also be applied which cuts off high accelerations and velocities to create smoother movements. The platform module can be seen in Figure 10.



Scaling of platform excursions

Factor 1 0

Safety settings

☑ Use safety filters

Amount 1 0.1 5

Settings

☑ Display 3D platform model

☑ Platform model represents physical state

☐ Cancel out yaw from input channel

Manual offsets

☐ Manual platform offset [m, deg] Reset sliders

| | | | |
|---|---|---|---|
| Sway (x) | 0 | -0.381 | 0.381 |
| Heave (y) | 0 | -0.323 | 0.248 |
| Surge (z) | 0 | -0.505 | 0.347 |
| Pitch (x) | 0 | -18 | 18 |
| Yaw (y) | 0 | -23 | 23 |
| Roll (z) | 0 | -18 | 18 |

Figure 10 Platform Module

### 3.2 Phidget Microcontroller Board

A microcontroller board from Phidget, Inc. (Alberta, Canada) was used to interface with D-Flow and the adaptive controls. The 1018_2-PhidgetInterfaceKit 8/8/8, which has 8 analog inputs, 8 digital inputs, and 8 digital outputs, was used. The board connects via a USB cable to the computer and via analog input to the adaptive controls. The relevant board specifications are shown in Table 1.

Table 1 Phidget Board Specifications [32]

| | |
|---|---|
| API Object Name | InterfaceKit |
| USB Voltage Min | 4.6 V DC |
| USB Voltage Max | 5.5 V DC |
| Current Consumption Min | 13 mA |
| Current Consumption Max | 500 mA |
| Available External Current | 487 mA |
| Recommended Wire Size | 16-26 AWG |
| USB Speed | Full Speed |
| Operating Temperature Min | 0 °C |
| Operating Temperature Max | 70 °C |
| Number of Analog Inputs | 8 |
| Analog Input Resolution | 10 bit |
| Input Impedance | 900 kΩ |
| Analog Input Voltage Min | 0 V DC |
| Analog Input Voltage Max | 5 V DC |
| 5V Reference Error Max | 0.5 % |
| Analog Input Update Rate Min | 1 samples/s |
| Analog Input Update Rate Max (4 Channels) | 1000 samples/s |
| Analog Input Update Rate Max (8 Channels) | 500 samples/s |
| Analog Input Update Rate Max (WebService) | 62.5 samples/s |

## 3.3 Controls

### 3.3.1 Adaptive Controls

CAREN is coupled to Advanced Electronic Vehicle Interface Technology (AEVIT) DBW controls from Electronic Mobility Controls (EMC©) [10]. These are the DBW controls used in USF's previous driving simulator. Figure 11 shows a small wheel device that controls the steering and a lever device that controls the gas and brake. These are equipped with potentiometers that send signals to servomotors that are normally connected to the steering column and pedals in a vehicle.

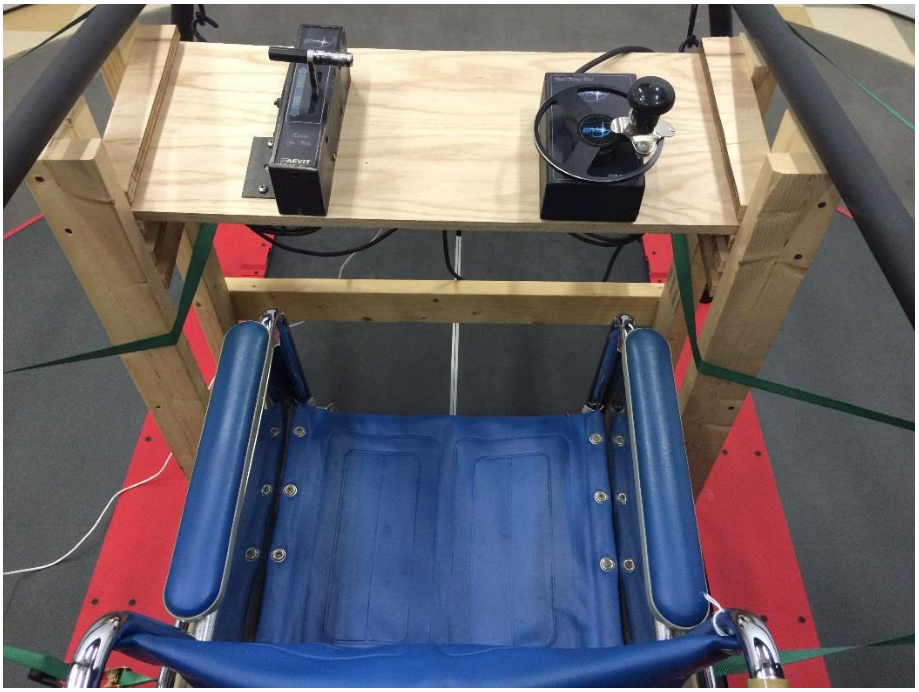


Figure 11 AEVIT Adaptive Driving Controls

Figure 12 shows the AEVIT system layout. The drive module is the central processing unit that takes the input from the controller used and sends an output to the appropriate servomotor. Also included are an information center that gives important information to the driver and a vehicle interface that obtains information from the vehicle. USF's previous system used a vehicle simulator module which simulates vehicle signals since an actual vehicle was not used.

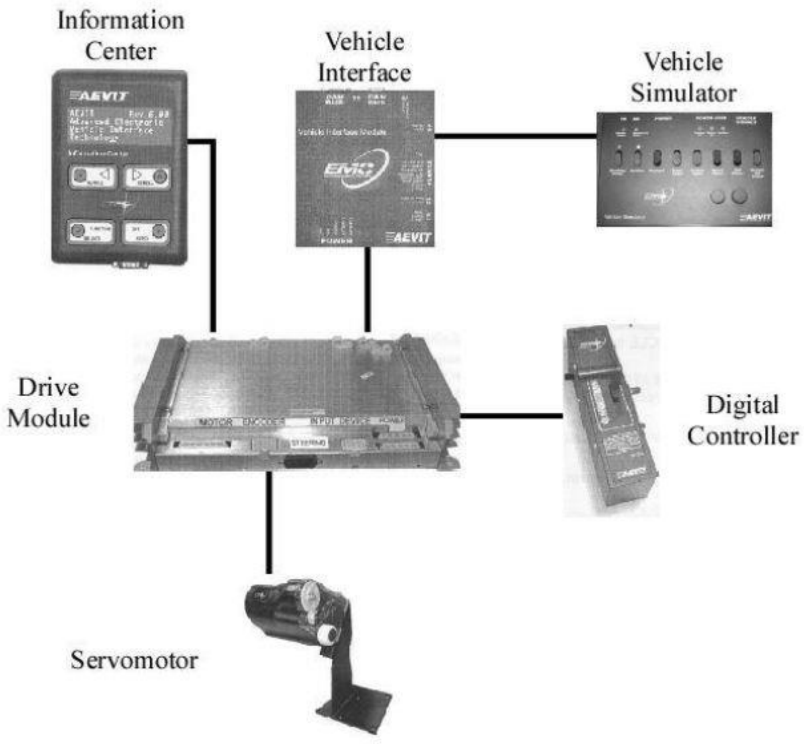


Figure 12 AEVIT System Layout [30]

For this study, the electrical voltage signals that go to the servomotors from the controllers were redirected to a Phidget microcontroller board which was connected to the CAREN system. For simplicity, only the controllers were used for this study and not the drive module, information center, vehicle simulator, or servomotor. The CAREN system uses these signals from the input devices as the input for gas/brake and steering. Figure 13 shows how the signals traveled from the adaptive controls to the CAREN system.

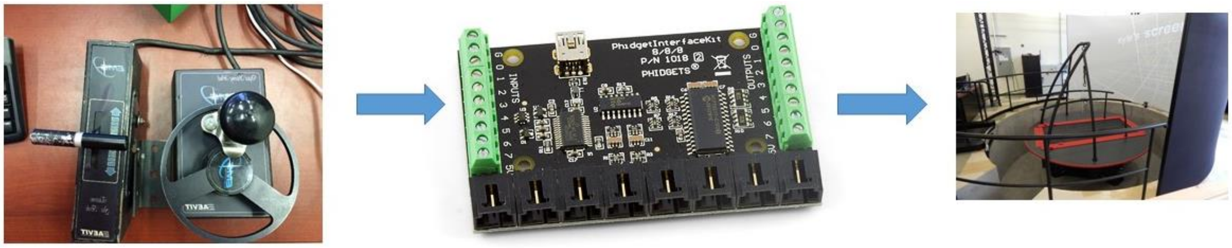


Figure 13 Signal Traveling from the Adaptive Controls to the CAREN System

When simply giving power to the potentiometers in the controllers and measuring the potentiometer’s outputs, noise was present and there was large overshoot. A low pass filter was able to smooth out the signal but was not able to get rid of the overshoot without having a large delay. Additional signal processing takes place in the AEVIT’s drive module in order to obtain a good signal. Since the controller’s outputs were not usable this way and the controllers needed to be used without the drive module, a different approach was used to get good signals from the controllers.

Pull-up resistors were used to obtain usable signals. The circuit board is shown in Figure 14 and the circuit diagram is shown in Figure 15. Electrical current travels from the Phidget’s voltage source to both a controller and to an analog input on the Phidget board. A resistor connected to the voltage source decreases this current. By applying Kirchhoff’s Current Law to the node after the resistor shows that some of the current will go to the controller and the rest will go to the analog input. Whenever there is a change in the controller’s circuit by changing the controller’s input position a different amount of current goes to the controller. This change can be measured by measuring the voltage going to the analog input. Measuring the signal this way produces a very stable signal that has no delay or overshoot.

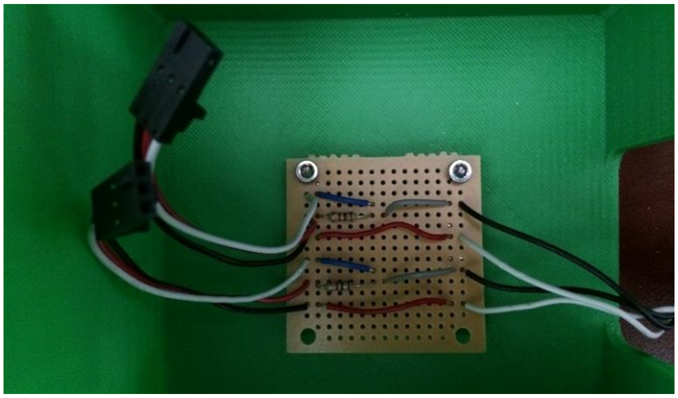


Figure 14 Circuit Board

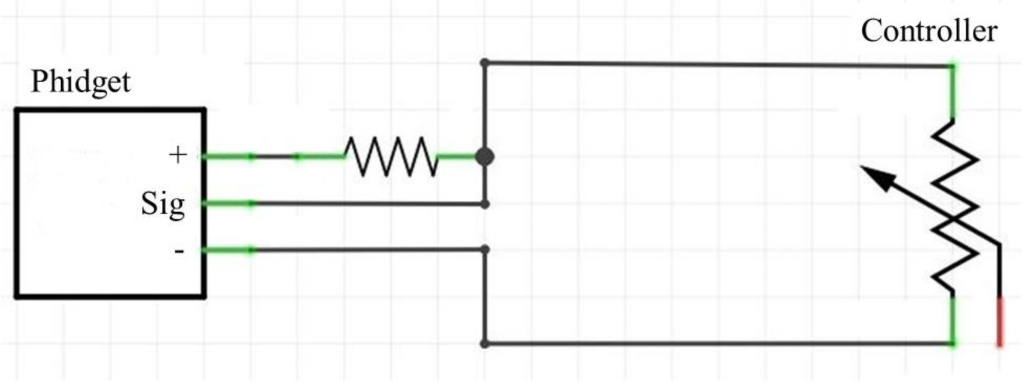


Figure 15 Circuit Diagram

### 3.3.2 Gaming Controls

Logitech Driving Force$^{TM}$ GT gaming controls are incorporated into the system when adaptive controls are not wanted. These mimic the controls found in non-adapted vehicles. They connects to the CAREN computer via USB. These controls can be seen in Figure 16. The steering wheel has a 900 degree wheel rotation, or goes 2.5 times around [33]. There are various buttons on the steering wheel that are programmable.

Figure 16 Driving Force GT Gaming Controls

### 3.4 Physical Set-Up

A table was built that can be carried on to the CAREN platform easily. It includes holes to attach the controls to. The gaming steering wheel can clamp to the edge. The table height is adjustable so that a wheelchair of different sizes can fit. The table top is set at an angle for comfort. Felt pads are attached to the bottom of the table legs so the treadmill is not damaged. Ratchet straps are used to strap a wheel chair and the table in place and a safety harness is used to secure the driver. This set-up is illustrated in Figure 17. CAD drawings of the table can be seen in Appendix B.

Figure 17 Driving Simulator Set-Up

# CHAPTER 4: THEORY

The virtual camera view movement and platform movement of the CAREN system were affected by the user's input. The virtual camera view movement was modeled by forces that would affect a real car in order to make the system more realistic while the platform movement was modeled by the classical motion cueing algorithm. This chapter discusses the equations involved in programming the virtual camera view and platform movements.

## 4.1 Notation

The variables that were used are described in Table 2.

Table 2 Variables Used

| **Variable** | **Description** |
|---|---|
| U | gas/brake force (N) |
| $n_A$ | gas/brake input position |
| B | resistive constant |
| M | mass (kg) |
| A | acceleration (m/sec^2) |
| V | velocity (m/sec) |
| P | position (m) |
| $C_A$ | gas/brake constant |
| $C_R$ | resistive constant |
| dt | time increment (sec) |
| W | weight (N) |
| CG | center of gravity |
| X | distance from back wheel to CG (m) |
| Y | distance from front wheel to CG (m) |
| H | distance from CG to ground (m) |
| L | length of wheel base (m) |
| $F_b$ | force on back wheel (N) |
| $F_f$ | force on front wheel (N) |
| R | turning radius (m) |
| $\Delta$ | steering angle (rad) |
| $n_S$ | steering input position |

Table 2 (Continued)

| | |
|---|---|
| $\Omega$ | angular velocity (rad/sec) |
| $C_S$ | steering constant |
| $\Theta$ | camera yaw position (rad) |
| A | tilt angle (rad) |
| F | low pass filtered acceleration (m/sec^2) |
| G | gain |
| Z | damping |
| $\omega_c$ | cut off frequency |
| $a_v$ | visual acceleration (m/sec^2) |
| $a_p$ | platform acceleration (m/sec^2) |
| S | sway position (m) |

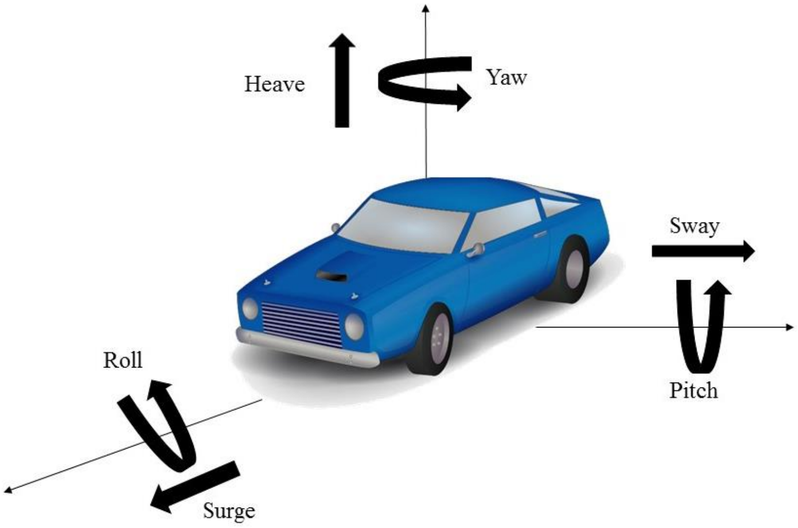


Figure 18 Movement Notation (Car Figure is Public Domain)

### 4.2 Virtual Camera View Movement

The virtual camera view movement consists of three motions: surge, pitch, and yaw. Surge, the forward motion of the virtual vehicle, was affected by the gas and brake inputs. Pitch was determined by the weight transfer between the virtual car’s front and back wheels that stem from the virtual car’s acceleration. Yaw was controlled by the steering wheel input.

### 4.2.1 Surge Movement: Gas and Brake

The surge movement of the camera view was modeled by longitudinal forces shown in Figure 19, based off of an online controls tutorial [34].

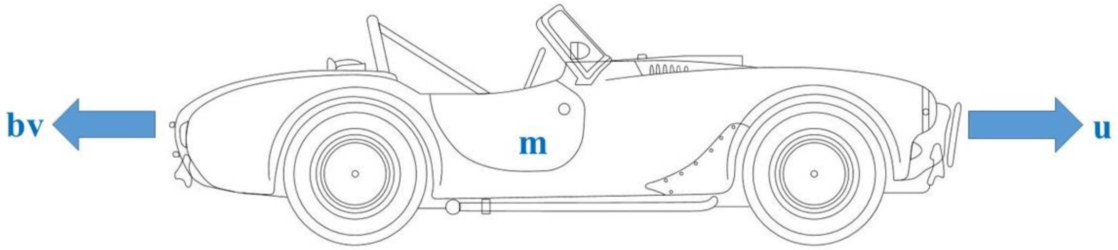


Figure 19 Longitudinal Forces (Car Figure is Public Domain)

In this diagram, u is the force created from the user's gas and brake controls and was controlled directly with the gas and brake control's input position, $n_A$. The other force, bv, represents the resistive forces of drag force and rolling force and was proportional to the car's speed. Summing up these forces and applying Newton's Second Law simplifies the equation to a first order differential equation,

$$\sum F = ma = m\dot{v} = u - bv \quad (1)$$

By solving for acceleration, this equation becomes

$$a = \left(\frac{1}{m}\right)u - \left(\frac{b}{m}\right)v = C_A n_A - C_R v \quad (2)$$

where $C_A = 1/m$, $C_R = b/m$, and $n_A = u$.

To determine the system's maximum velocity value, the acceleration Equation (2) is set to zero and velocity is calculated. Since the maximum velocity happens when gas's input position is at its maximum value of 1, the equation for maximum velocity is,

$$v_{max} = C_A / C_R \quad (3)$$

By replacing $C_A$ in equation 2 with the $C_A$ in Equation 3, the acceleration equation becomes,

$$a=C_R(v_{max}n_A-v) \tag{4}$$

It can be seen that acceleration is proportional to the $C_R$ value.

By specifying the acceleration constant, $C_R$, and maximum velocity, $C_A$ was solved for and the system behaved according to Equation 2. The virtual car's maximum speed, the acceleration used to reach the maximum speed, and the deceleration used to come to a stop, were programmable which affected how the system responded.

Velocity was found by integrating the acceleration from Equation (2) over time and, similarly, position was found by integrating position over time. Using Euler's method for numerical integration,

$$v_i=v_{i-1}+(a\times dt) \tag{5}$$

$$p_i=p_{i-1}+(v\times dt) \tag{6}$$

where $v_{i-1}$ and $p_{i-1}$ are the car's current velocity and position, respectively, and $v_i$ and $p_i$ are the car's next velocity and position, respectively. The term dt is the time increment between loops, which is approximately 3 milliseconds for the CAREN system. The velocity values found were fed back into Equation (2) in order to continue solving for acceleration while the position values were used to control the virtual camera view position.

### 4.2.2 Pitch Movement: Weight Transfer

As a real car accelerates and decelerates, weight is transferred between its front and back wheels. Depending on how much the virtual car accelerated or decelerated, the virtual camera view position pitched in the corresponding direction. A free body diagram of the forces acting on the car, disregarding lateral forces, is shown in in Figure 20.

Doing a moment balance about each of the wheels results in the following equations:

$$F_b=W\left({}^{y}/_{L}\right)+ma\left({}^{h}/_{L}\right) \tag{7}$$

$$F_f = W\left(\frac{x}{L}\right) - ma\left(\frac{h}{L}\right) \tag{8}$$

Looking at these equations, it can be seen that when there is no acceleration and when the center of gravity is directly in the middle of the wheel base, there is equal weight on each wheel. As a real car accelerates, weight is transferred from the front to the back wheel. The virtual car accelerating resulted in the virtual camera position pitching backwards. As a real car decelerates, weight is transferred from the back to the front wheel. The virtual car decelerating resulted in the virtual camera position pitching forwards.

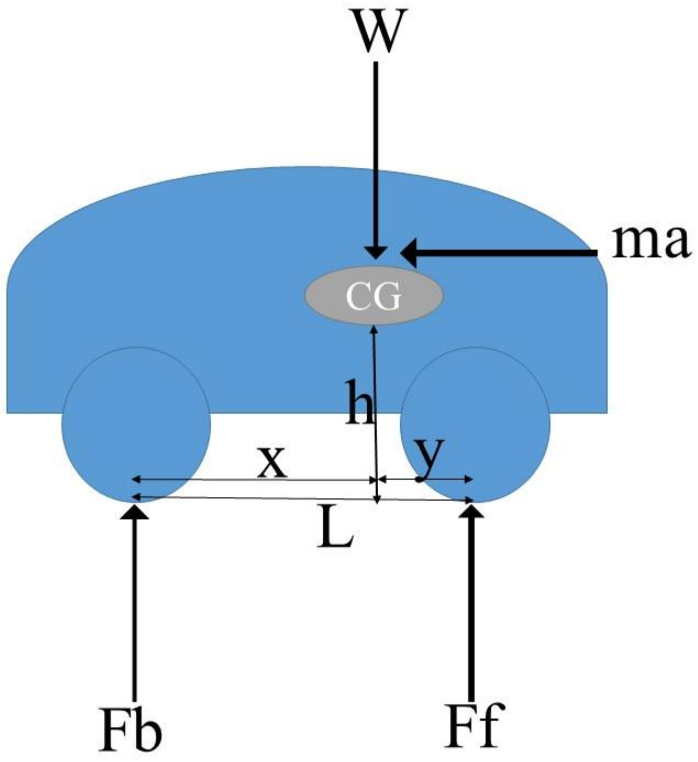


Figure 20 Free Body Diagram

### 4.2.3 Yaw Movement: Steering

The user turning the steering wheel simulated the front wheel turning at an angle, δ. As the front wheel turns, the car moves in a circular path with the center of the circle being the location where lines drawn through the center of the wheels intersect. This is illustrated in Figure 21. The radius of this circular path was calculated using geometric properties.

$$R=L/\sin(\delta) \tag{9}$$

As the car moves, its orientation changes by an angular velocity, $\omega$,

$$\omega=\frac{v}{R} \tag{10}$$

Substituting equation (9) into equation (10),

$$\omega=\frac{v\sin(\delta)}{L} \tag{11}$$

By approximating $\sin(\delta) = n_s$ and simplifying $1/L = C_S$,

$$\omega=vn_sC_S \tag{12}$$

where $C_s$ is a steering constant which determines the steering sensitivity, or how much the virtual car turns for a given steering input. This steering constant is a variable that changes according to the steering input. This is found frequently in rack and pinion systems where the teeth on the rack are variable in order to give more mechanical advantage as the steering wheel moves away from the center position. For example, at small steering inputs when the steering wheel is near the center, $C_S$ is smaller so the driver does not over steer. At large steering inputs, such as when a turning maneuver is being done, $C_S$ is becomes larger so that it is easier for the driver to turn.

Similarly to the car's straight line velocity and position, the car's angular position was calculated using Euler's method for numerical integration.

$$\theta=\theta+(\omega\times dt) \tag{13}$$

This angular position controlled the virtual camera's yaw position.

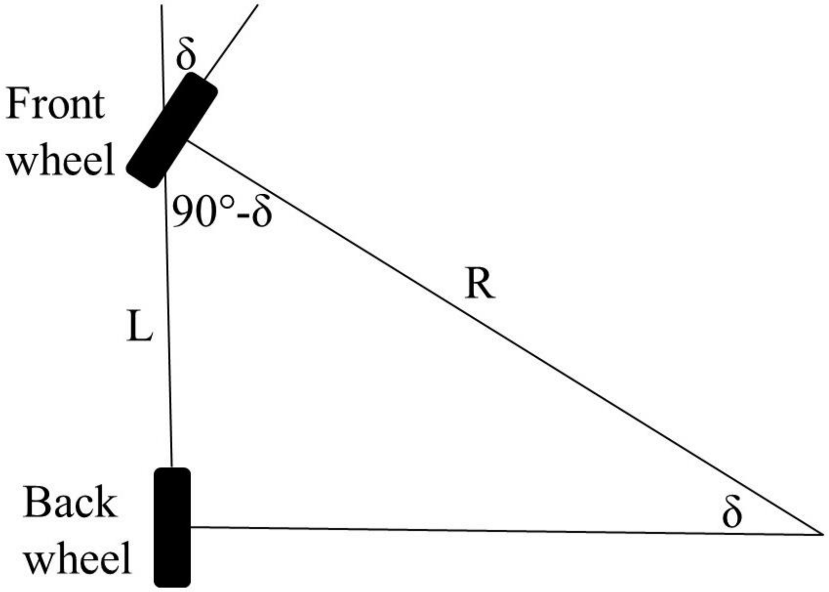


Figure 21 Steering Geometry

### 4.3 Platform Movement

Motion cueing transitions the visual accelerations calculated in the previous sections to dynamic accelerations produced by the motion platform. This study uses the classical motion cueing algorithm because it is easiest to implement as a starting point.

### 4.3.1 Motion Cueing Literature

A study using the DLR simulator described the classical motion cueing algorithm as consisting of four main parts [35]:

1. *Scaling.* Input accelerations, both longitudinal and centripetal, as well as input angular velocities are scaled down to values that the simulator can handle.
2. *Filtering.* The scaled accelerations and angular velocities go through high pass filters to get rid of low frequencies so that only the higher frequencies remain. These high frequencies do not last for a long time so the end of the workspace will not be reached, as long as the correct filter parameters are chosen. The filter parameters are often chosen from a "worst case" scenario involving the highest accelerations possible. The scaled

accelerations also go through low pass filters to get rid of high frequency accelerations so only the low frequency accelerations remain. These low frequency accelerations are used during the tilt coordination which provides an acceleration through a tilt of the motion platform.

3. *To Positions/Angles.* High frequency accelerations are transformed to surge and sway positions by double integrators. Low frequency accelerations are transformed to pitch and roll angles using tilt coordination. High frequency angular velocities are transformed to yaw angles by a single integrator.
4. *Washout.* Additional washout filters are used to bring the platform positions back to their neutral positions.

This classical motion cueing algorithm is illustrated in Figure 22 as a block diagram.

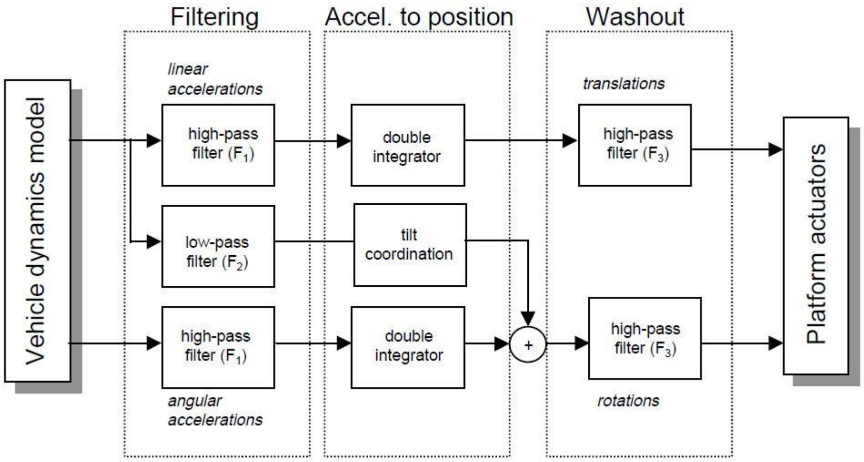


Figure 22 Classical Motion Cueing Algorithm Block Diagram [36]

### 4.3.2 Block Diagram

The block diagram that this study used was based off of the classical algorithm described above but with some modifications:

- Only longitudinal and centripetal accelerations were used as inputs. This ensures that both longitudinal and centripetal forces are accounted for. Angular velocity which would simulate angular movement was not used at this time.
- Washout filters were not used because the platform positions naturally came to their neutral positions after executing movement.
- Instead of a high pass filter, a mathematical function was used to calculate sway movement because of instability of the filtering.

The block diagram used in this study can be seen in Figure 23. It is also broken up into four parts:

1. *Input.* The inputs are longitudinal and centripetal acceleration calculated from the virtual camera view movement.
2. *Filtering.* The longitudinal acceleration is high pass filtered to retain only the high frequency movement and low pass filtered to retain only the low frequency movement. The centripetal acceleration is sent through a mathematical function to determine sway movement and through a low pass filter to retain only the low frequencies.
3. *To Positions/Angles.* The longitudinal acceleration that was high pass filtered is double integrated to obtain a positional value. The longitudinal and centripetal accelerations that were low pass filtered are transformed to angular values through tilt coordination.
4. *Output.* Longitudinal acceleration is simulated through surge and pitch movements of the platform while centripetal acceleration is simulated through sway and roll movements of the platform.

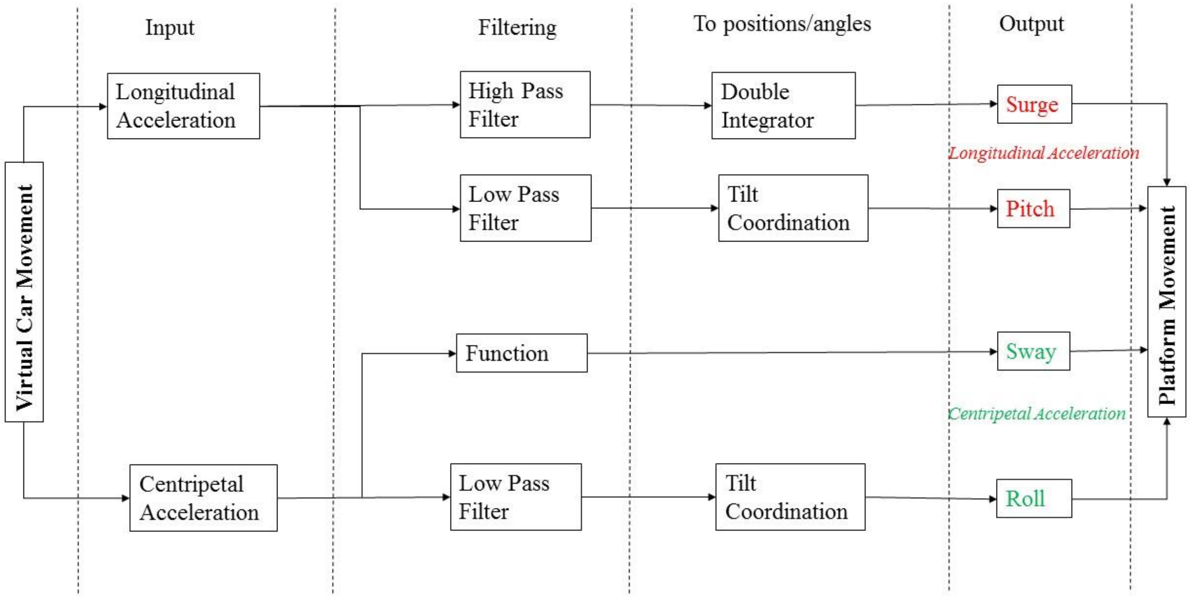


Figure 23 Block Diagram Used in this Study

### 4.3.3 Tilt Coordination

Tilt coordination mentioned above involves providing small tilt angles to the user to simulate acceleration. This works on the principle that the human perception system cannot detect motion below a certain threshold. If the head is tilted at a certain angle with respect to gravity as in Figure 24, the perceived gravity will be different than the actual gravity vector. The actual gravity vector will be perceived as an acceleration without actually accelerating, as long as a visual acceleration is provided.

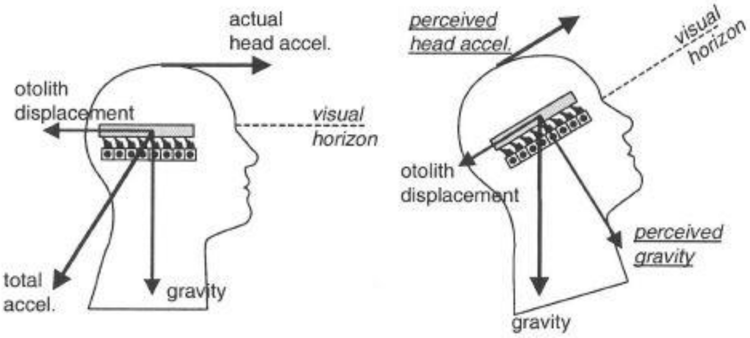


Figure 24 Tilt Coordination [36]

The longitudinal and centripetal accelerations were sent through low pass filters to extract the small accelerations. These smaller accelerations are for sustained cues that affect the platform's tilt and roll movements through the tilt coordination. After the low frequency accelerations were found, tilt coordination was calculated using the equation

$$\alpha = \sin^{-1}(f/9.81) \tag{14}$$

where f is the low pass filtered accelerations and α is the platform tilt angle.  This equation was found through the geometry of the tilt coordination (see Figure 24). A rate limiting algorithm is also used in order to limit the angular velocity of the tilt so that the tilt and roll is perceived as an acceleration rather than a rotation because of the fact that humans cannot perceive angular rotations below a threshold.

### 4.3.4 Low Pass Filtering

The longitudinal and centripetal accelerations were sent through second order low pass filters to extract the small accelerations that were used for the tilt coordination. A second order Butterworth filter was used that reduces signals that have a higher frequency than the specified cut-off frequency. An inherent behavior in the Butterworth filter is that as the cut-off frequency decreases, so does the latency. A trial and error process is used to determine the cut-off frequencies and gains.

### 4.3.5 High Pass Filtering

The longitudinal acceleration was sent through a second order high pass filter to extract the large accelerations. These larger accelerations are for initial acceleration cues that affect the platform's surge movement. The transfer function associated with this high pass filter is

$$TF = \frac{a_p}{a_v} = \frac{Gs^2}{s^2 + 2\zeta w_c s + w_c^2} \tag{15}$$

where G, $\zeta$, and $\omega_c$ are parameters that can be changed to affect the filter's behavior, $a_v$ is the visual acceleration, and $a_p$ is the platform acceleration. The process of choosing these parameters is a trial and error process of changing parameters values and seeing how it affects the simulator's realism. The filtered acceleration is integrated twice to obtain the surge position. With this filtering, the platform surge position naturally comes to its neutral position after executing movement so no washout filter is necessary.

### 4.3.6 Sway Mathematical Function

After passing the centripetal acceleration through various high pass filters and washout filters, no stability was able to be found. The sway position would often drive to a very high value at random times. This may because of the unsteadiness of the centripetal acceleration values. Instead, a mathematical formula was used to calculate the sway position based on the steering input and velocity, both of which are factors in centripetal acceleration. The formula used to calculate sway position is,

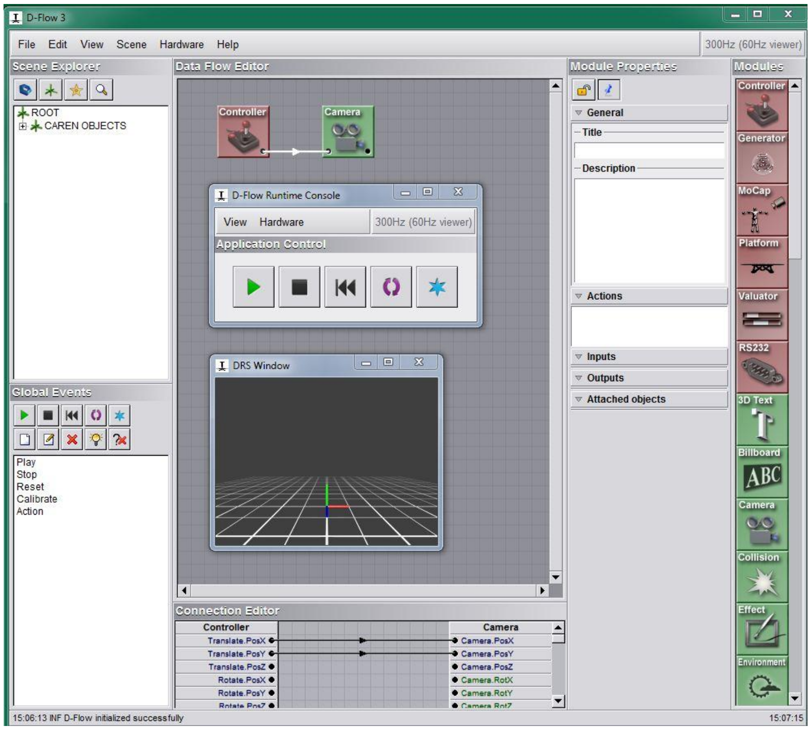
$$s=\frac{n_s v}{v_{max}}\times s_{max} \tag{16}$$

where $n_s$ is the steering input, v is the virtual car's velocity, $v_{max}$ is the maximum speed expected, and $s_{max}$ is the maximum sway position. In this equation, $n_s v/v_{max}$ determines the percentage of the maximum sway position the platform is at. While there is no washout of the sway position, it will never go past the platform's sway limit.

# CHAPTER 5: SOFTWARE

## 5.1 D-Flow

D-Flow is the software used by the CAREN system. The D-Flow screen can be seen in Figure 25. The various sections of the screen that are shown are described in Table 3.



15:06:13 INF D-Flow initialized successfully

Figure 25 The D-Flow Screen

Table 3 D-Flow Section Descriptions

| Section | Description |
|---|---|
| Data Flow Editor | The data flow editor shows all modules used and the connections between them. |
| Connection Editor | The connections between modules can be edited by clicking on the lines that connect them. Under the connection editor, wires can be created, moved, and deleted. |

Table 3 (Continued)

| | |
|---|---|
| Modules | All the modules available for use are displayed here. |
| Module Properties | Module properties, inputs, and outputs are displayed here. |
| Scene Explorer | The scene explorer lists all of the objects and scenes that are in the virtual environment. |
| Global Events | All of the events used in the application are listed here. |
| DRS Window | The DRS Window displays the virtual environment. |
| Runtime Console | The runtime console controls the application and its parameters. |

The software interface is modular in design with inputs and outputs going from module to module through connections. Each module has a user interface for its parameters to be altered. Commonly used modules are described in Table 4.

Table 4 Module Descriptions

| ***Module*** | **Description** | **Use** |
|---|---|---|
| Controller | Used with Windows supported input devices like joysticks. Outputs include the values of the device’s buttons. | A gaming steering wheel and pedals was used as an input device option. |
| Phidgets | Reads data coming from ‘Phidget’ sensors and microcontroller boards. | A Phidget microcontroller board was used to interface with adaptive controls. |
| Platform | Controls the six degrees of freedom, scaling, safety filters, and offsets of the motion base. | The platform was used to provide dynamic feedback. |

Table 4 (Continued)

| | | |
|---|---|---|
| Valuator | Six parameters can be controlled with sliders. The first two parameters can be controlled with a 2D value box. | The valuator was another input device option. Gas/brake and steering were controlled with the 2D value box. |
| 3D Text | Creates a 3D text in the virtual environment. Size and appearance can be changed. | Used to display the driver’s speed and number of collisions. |
| Camera | Controls the position and orientation of the user’s viewpoint. | Used to simulate the driver driving through the virtual environment |
| Collision | Detects collisions between different objects of the scene. | Used to detect when a driver hits another car or runs a red light. |
| Environment | Controls the environment settings. Background and ambient color, fog settings, and shadows can be set. | Used to change the brightness of the virtual environment and make the sky look blue. |
| Effect | Creates a visual effect in the virtual environment. | A visual effect was used to let the driver know there was a collision. |
| Object | Controls the position, orientation, and scaling of objects in the virtual environment. | Objects such as stop signs, traffic lights, and cars were positioned using this module. |
| Counter | Counts how many times an event happens. | The number of collisions that occurred was counted. |
| Event | When a specific condition is met, an event can be broadcasted. | Used to broadcast when a collision has occurred and when a traffic light is red. |
| Expression | Used to calculate expressions between modules. Can do arithmetical, conditional, geometrical, and exponential expressions. | Used to process input device values. Also used to calculate road and car positions in the endless highway scene. |

Table 4 (Continued)

| | | |
|---|---|---|
| Script | Used to write scripts in the Lua scripting language. | The camera and platform movement based on the input were calculated using a script module. |
| Sound Player | Plays sounds in the .wav format. Volume, pitch, and source position can be controlled. | The sound of a car engine was used and its pitch was controlled based on velocity. |
| Stopwatch | Able to keep track of how much time has passed and can countdown from a certain time. Able to trigger events at a particular time. | Used to control when a traffic light changes to red, yellow, and green. Used to determine how long an Effect module lasts. |
| Switch | Switches between sets of channels. Can be ‘Many to One’ where one of multiple inputs can be selected or ‘One to Many’ where one input is sent to multiple outputs. | All input devices are connected to a ‘Many to One’ Switch module and the user selects which input to use. |
| Parameter | Controls parameters in the Runtime Console. Sliders, lists, checkboxes, buttons, and separators can be used. | Parameters such as maximum speed, steering sensitivity, acceleration, and maximum platform pitch were altered. |
| Record Data | Used to record data to a .txt file. | Used to record data during testing the system. |

## 5.2 Scene Development

Driving scenes were created using Google SketchUp 3D modeling software. Components of the scene such as cars, stop signs, and buildings were either drawn using the 3D modeling tools or they were imported from SketchUp’s 3D warehouse, a source of free 3D models. After a scene was created in Google SketchUp, the file was exported to a mesh file using OgreXML Converter. A mesh is a collection of polyhedral shapes that make up a 3D model. After a scene was exported, it was imported into D-Flow to be used in the driving applications. The two driving scenes that were created are an endless highway scene and a city scene and will be described in detail in sections 5.5 and 5.6, respectively.

### 5.3 Camera Movement

The virtual camera movement was programmed in D-Flow using the modules shown in Figure 26.

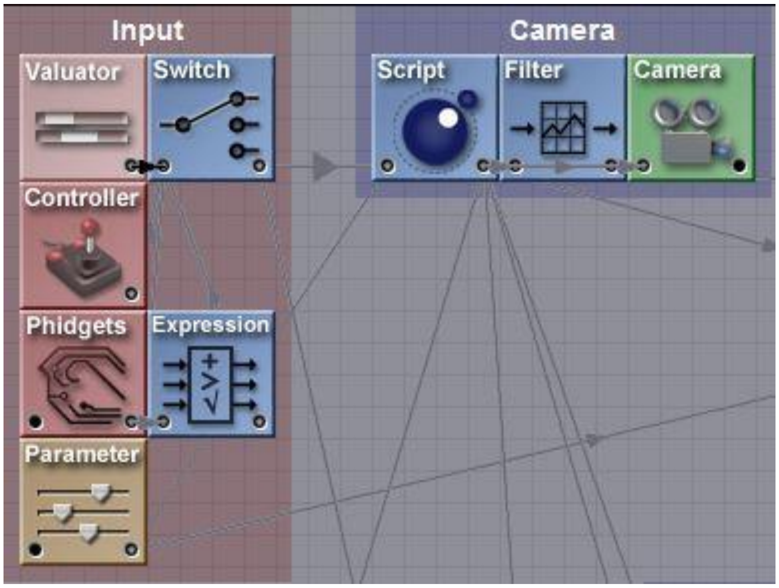


Figure 26 Overview of Camera Movement Programming

First, the input values were obtained from one of three input devices: an on-screen valuator, the Logitech gaming controls, or AEVIT adaptive controls. The on-screen valuator is controlled with the computer mouse inside a box shown on the computer screen (Figure 27). Gas is applied as the cursor moves towards the top of the box and brake is applied as the cursor moves towards the bottom of the box. Steering is controlled by moving the cursor to the right and left sides of the box. The Logitech gaming controls connect to the computer via a USB connection. The controls interface with the controller module where input position values can be obtained. Voltage values from the AEVIT adaptive controls travel to a Phidget board which connects to the computer via USB. The input values from the Phidget module go to an expression module which calibrates the values to numbers ranging from -1 to +1. This is done by recording the values obtained when the adaptive controls are at their center, maximum, and minimum positions.

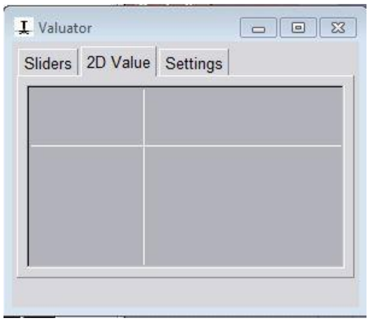
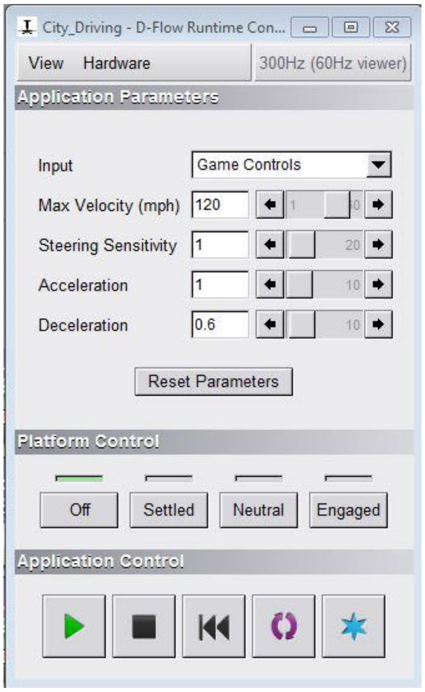


Figure 27 On-Screen Valuator Option

The runtime console, shown in Figure 28, is where the user chooses the input device, maximum velocity, acceleration sensitivity, deceleration sensitivity, and steering sensitivity. The input device option from the runtime console and the input values from the three input devices are sent to a ‘many to one’ switch module. This switch module outputs the correct input values depending on which option is chosen in the runtime console.

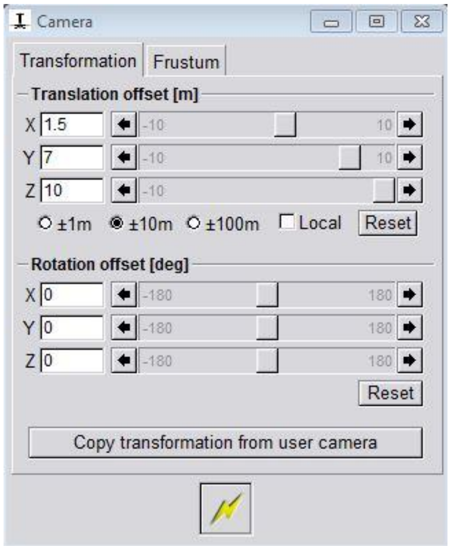


Input: Game Controls
Max Velocity (mph): 120
Steering Sensitivity: 1
Acceleration: 1
Deceleration: 0.6

Figure 28 Runtime Console for Driving Applications

After the input values were obtained, they were sent to a script module which transformed the values to virtual camera positions. This script is located in in Appendix C. The first part of the script initializes values, defines the inputs, and defines constants. Then, the script calculates the camera positions using the equations described in Chapter 4. Finally, the script outputs camera positions to the camera module and outputs longitudinal and centripetal acceleration to be used in calculating platform movement.

The camera module settings can be seen in Figure 29. The camera rotation is selected to be about the car’s current position rather than the center of the scene environment. The offsets were chosen based on the desired initial virtual camera view position.



Translation offset [m]
X 1.5
Y 7
Z 10
○ ±1m ● ±10m ○ ±100m ☐ Local

Rotation offset [deg]
X 0
Y 0
Z 0

Figure 29 Camera Module Settings

### 5.4 Platform Movement

Platform movement consists of surge, tilt, roll, and sway. Surge and tilt movement were created from the visual longitudinal acceleration while roll and sway movement were created from the visual centripetal acceleration. The data flow is shown in Figure 30. Each movement is discussed in more detail in the following sections.

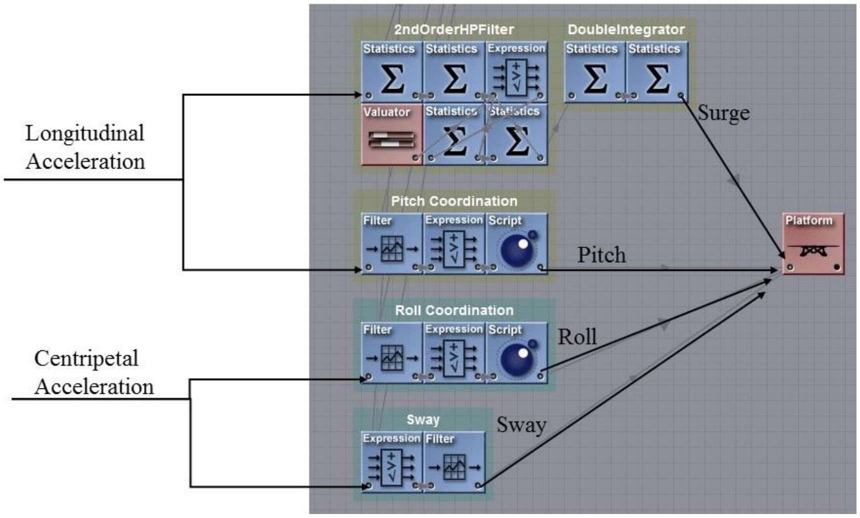


Figure 30 Platform Data Flow

### 5.4.1 Surge

The platform surge movement was programmed in D-Flow using a numerical approach. The inverse Laplace transform of Equation (15) was first taken and the result was a second order differential equation shown by

$$G\ddot{a}_v(t)=\ddot{a}_p(t)+2\zeta\omega_c\dot{a}_p(t)+\omega_c^2a_p(t) \tag{17}$$

Solving for the second derivative of the platform acceleration gives

$$\ddot{a}_p(t)= G\ddot{a}_v(t)-2\zeta\omega\dot{a}_p(t)-\omega^2a_p(t) \tag{18}$$

Figure 31 shows the flow of signals through D-Flow. The visual linear acceleration is differentiated twice through two statistics modules. The filter parameters are chosen with a valuator module and fed to an expression module. An expression module calculates Equation (18) and the result, the second derivate of platform acceleration, is integrated twice to obtain the first derivative of platform acceleration and the platform acceleration. The results are fed back to the expression module to continue calculating. The platform acceleration is finally integrated twice to obtain platform surge position.

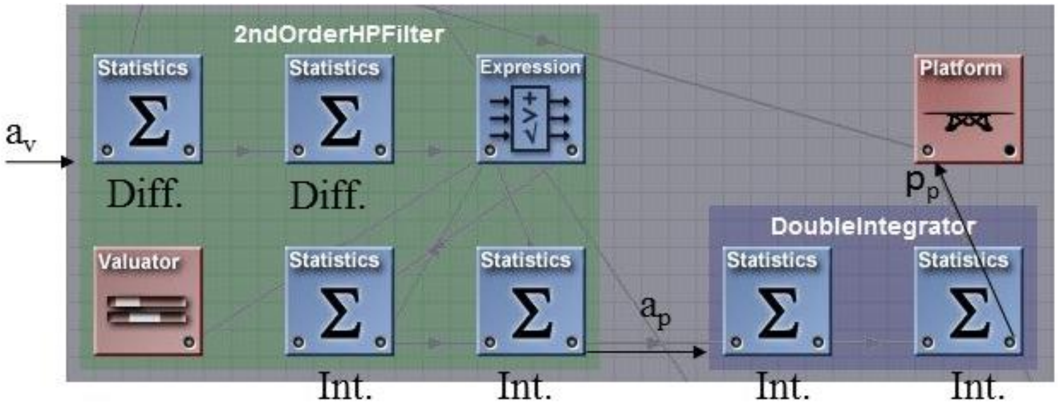


Figure 31 Programming Platform Surge Position in D-Flow

### 5.4.2 Tilt and Roll

Figure 32 shows the flow of signals through D-Flow to calculate platform tilt and roll angles. The visual acceleration is first sent through a second order Butterworth filter module where the cut-off frequency is set. Longitudinal and centripetal acceleration are outputted from the filter for tilt and roll, respectively. The tilt or roll angle can then be calculated using an expression module and Equation (14). Finally, a rate limiting algorithm is used to keep the tilt velocity below 0.3°/s, which was determined experimentally. The rate limiting algorithm can be seen in Appendix C.

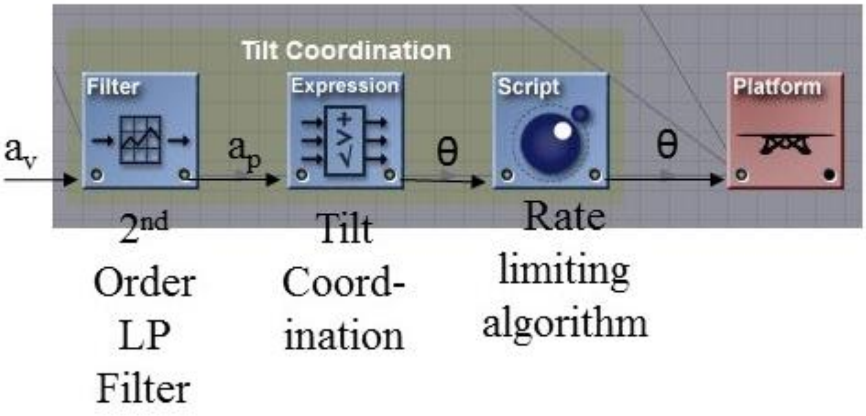


Figure 32 Programming Platform Tilt Position in D-Flow

### 5.4.3 Sway

Platform sway movement was calculated using Equation (16). The equation was written in an expression module with steering input and velocity as inputs and sway position as output. The sway position was then sent through a filter module to make it smoother before going to the platform module.

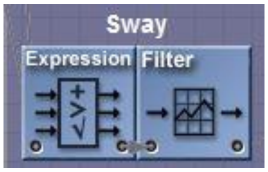


Figure 33 Modules Used for Platform Sway

## 5.5 Highway Scene Features

The highway environment includes a four lane highway and four vehicles, shown in Figure 34. It also displays the driver's speed and number of collisions. It was designed to help with driving stability, by maintaining speed and lane position, as well as obstacle avoidance. There are several features that are unique to the highway scene.

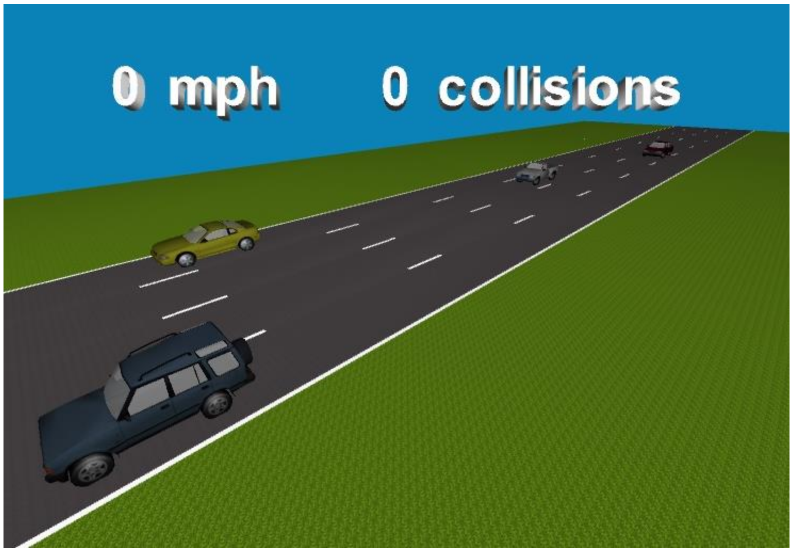


Figure 34 Highway Environment

The highway endlessly loops. The environment is made up of three identical highway sections that move in a loop past the driver. This concept is based off of a D-Flow tutorial from Motek Medical [31], shown in Figure 35. In this scene, the camera does not move. The highway sections move past the camera at the speed specified in the camera movement script. When a tile gets to a certain point, it flips back behind the other two tiles to create the effect that the camera is moving through the environment.

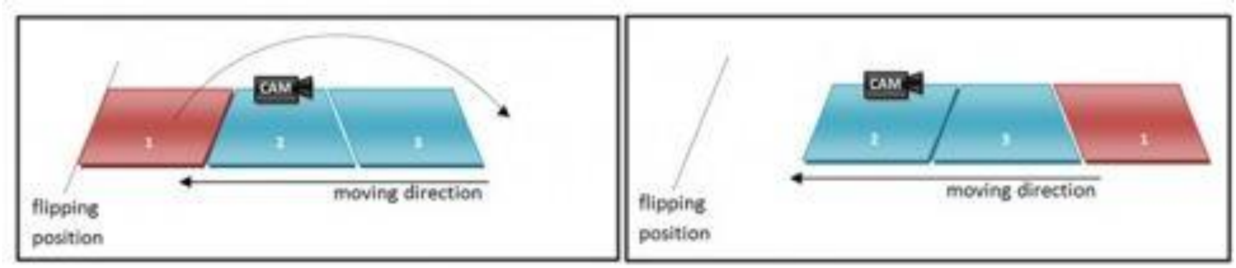
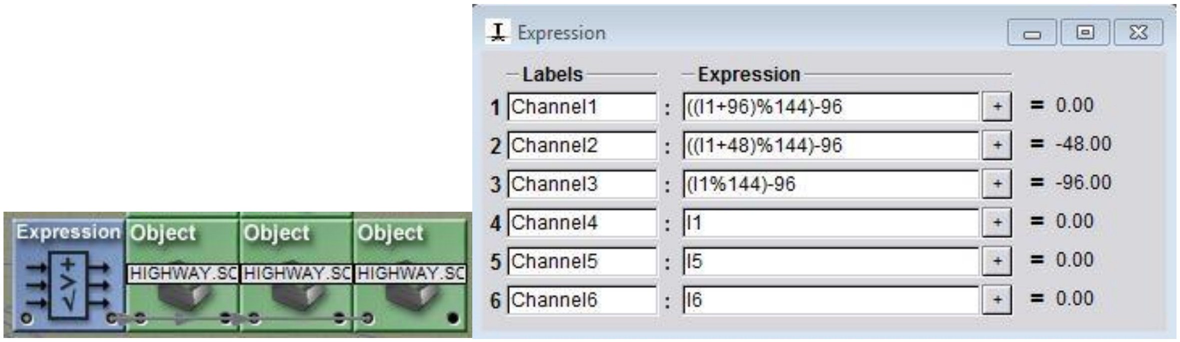


Figure 35 Endless Highway Effect [31]

The modules used for this feature and the expression module properties are shown in Figure 36. The input to the expression module, I1, is the virtual camera surge position. Each section has a length of 48 meters and the three sections are offset by 0 meters, 48 meters, and 96 meters, respectively. Once a tile travels 144 meters, it is set back to its original position. Each channel outputs to a different highway section.

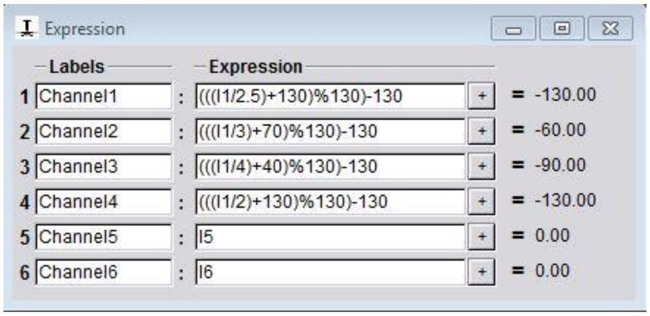


| | Labels | | Expression | | |
|---|---|---|---|---|---|
| 1 | Channel1 | : | ((I1+96)%144)-96 | + | = 0.00 |
| 2 | Channel2 | : | ((I1+48)%144)-96 | + | = -48.00 |
| 3 | Channel3 | : | (I1%144)-96 | + | = -96.00 |
| 4 | Channel4 | : | I1 | + | = 0.00 |
| 5 | Channel5 | : | I5 | + | = 0.00 |
| 6 | Channel6 | : | I6 | + | = 0.00 |

Figure 36 Modules and Expression Properties for Endless Highway Effect

The virtual camera does not move in the surge direction but is instead illustrated by the endless highway effect. It does, however, still move in the sway direction and susceptible to leaving the horizontal bounds of the highway. To prevent this, part of the camera script includes code that checks to see if the camera's sway position is within the horizontal limits of the highway. If it is not, the camera's sway position is set back to the edge of the highway. This ensures that the driver always stays on the road.

The other four cars move in a similar fashion to the highway sections using another expression module. The only difference is that their speed is reduced by a certain factor so that it appears that they are moving relative to the road and each other but never faster than the driver. The expression module properties used for the four cars can be seen in Figure 37. The input, virtual camera surge position, is reduced by the factors 2, 2.5, 3, and 4 which make the other cars seem like they are traveling at different speeds. The four cars are offset by 40 meters, 70 meters, and 130 meters. Once a car travels 130 meters, it is set back to its original position.



|  | Labels |  | Expression |  |  |
|---|---|---|---|---|---|
| 1 | Channel1 | : | (((I1/2.5)+130)%130)-130 | = | -130.00 |
| 2 | Channel2 | : | (((I1/3)+70)%130)-130 | = | -60.00 |
| 3 | Channel3 | : | (((I1/4)+40)%130)-130 | = | -90.00 |
| 4 | Channel4 | : | (((I1/2)+130)%130)-130 | = | -130.00 |
| 5 | Channel5 | : | I5 | = | 0.00 |
| 6 | Channel6 | : | I6 | = | 0.00 |

Figure 37 Expression Module Properties for the Four Other Cars

Collisions between the driver and other cars are detected using a collision module. A counter module counts the number of collisions and displays it to the driver. When there is a collision, the colors of the scene change colors for a set period of time using an effect module (see Figure 38) for a certain amount of time, specified by a stopwatch module. A hitting sound is also heard using a sound player module.

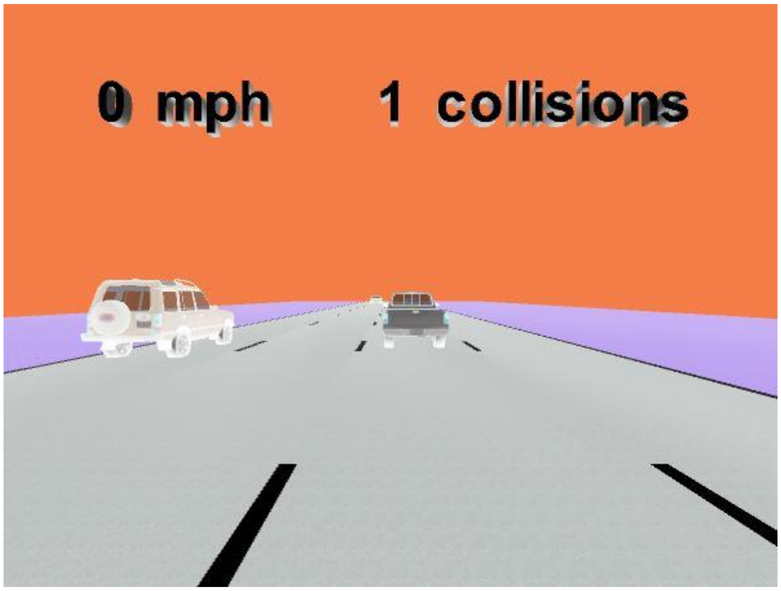
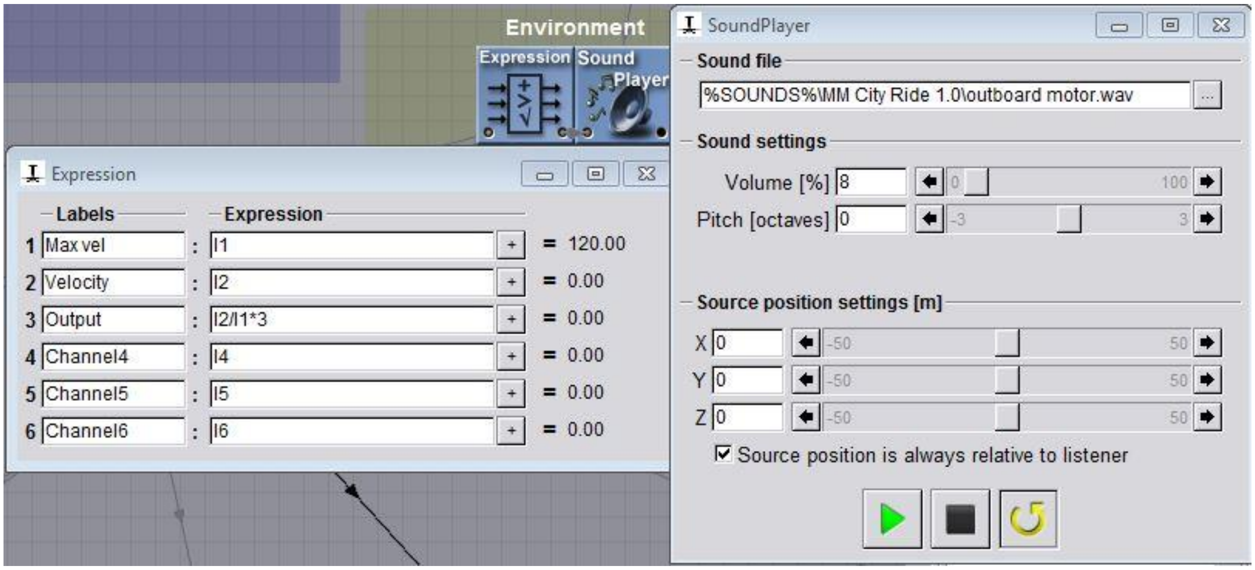


Figure 38 Collision Effect

In both the highway scene and the city scene, a motor sound is presented to the driver using a sound player module. The pitch property of the sound player module is controlled by the user's speed so that the pitch increases when the car speeds up and is lowered when the car slows down. These modules and their properties can be seen in Figure 39.



|  | Labels |  | Expression |  |
|---|---|---|---|---|
| 1 | Max vel | : | l1 | = 120.00 |
| 2 | Velocity | : | l2 | = 0.00 |
| 3 | Output | : | l2/l1*3 | = 0.00 |
| 4 | Channel4 | : | l4 | = 0.00 |
| 5 | Channel5 | : | l5 | = 0.00 |
| 6 | Channel6 | : | l6 | = 0.00 |

Sound file

%SOUNDS%\MM City Ride 1.0\outboard motor.wav

Sound settings

Volume [%] 8 (0–100)

Pitch [octaves] 0 (-3–3)

Source position settings [m]

X 0 (-50–50)

Y 0 (-50–50)

Z 0 (-50–50)

☑ Source position is always relative to listener

Figure 39 Sound Modules and Properties

## 5.6 City Scene Features

The city scene environment consists of four blocks with stop lights in the middle intersection and stop signs at the outer intersections. A top view of this environment is shown in Figure 40 and a driver point of view is shown in Figure 41. The purpose of this scene is for users to adhere to the rules of the road by obeying stop light rules.

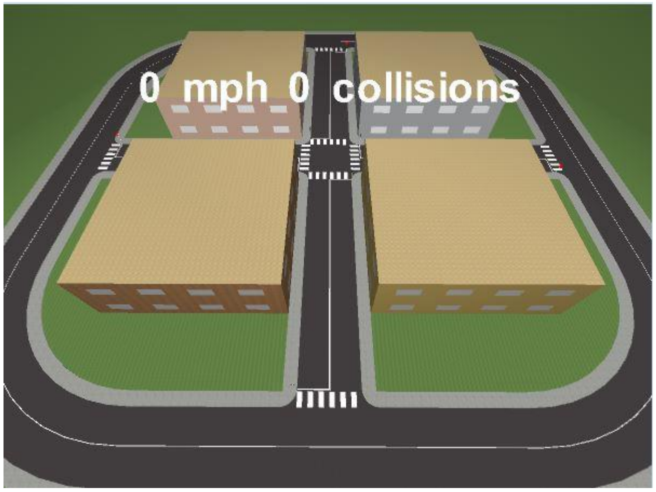


Figure 40 Top View of City Environment

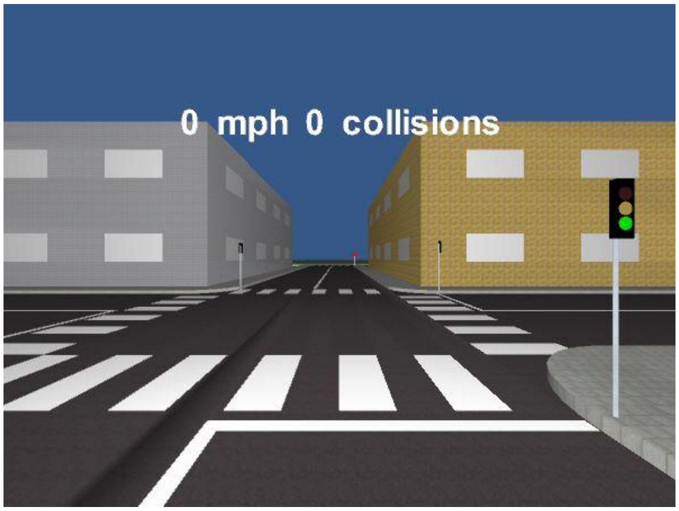


Figure 41 Driver Point of View in the City Scene

One feature unique to the city scene is the four color-changing stop lights in the middle intersection. These four stop lights are programmed using the timing diagram shown in Figure 42. The stop lights that are opposite of each other are grouped together.

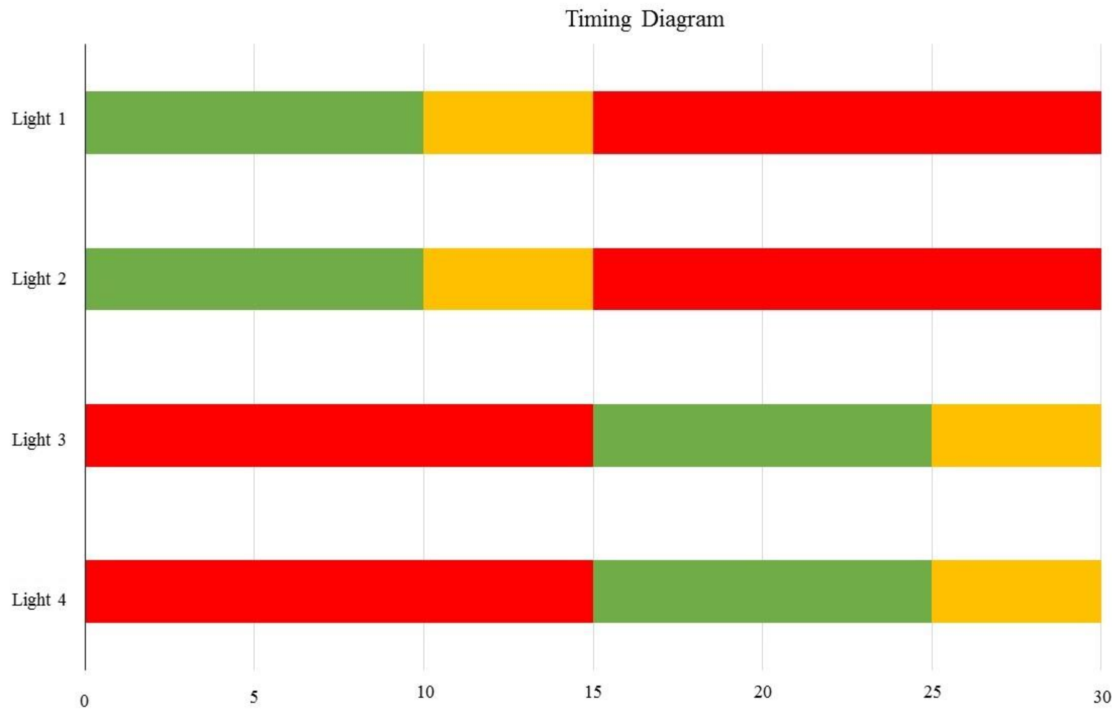


Figure 42 Timing Diagram for Stop Lights

A stop watch module keeps track of the time and sends it to event modules, shown in Figure 43. These event modules broadcast the events for turning the lights green, yellow, and red when its timing condition is true. At each of the four stop light locations, there are actually three stop light objects. One is green, one is yellow, and one is red. The objects show or hide according to which event is true. For example, the green object shows while the yellow and red objects hide when the green light event is true.

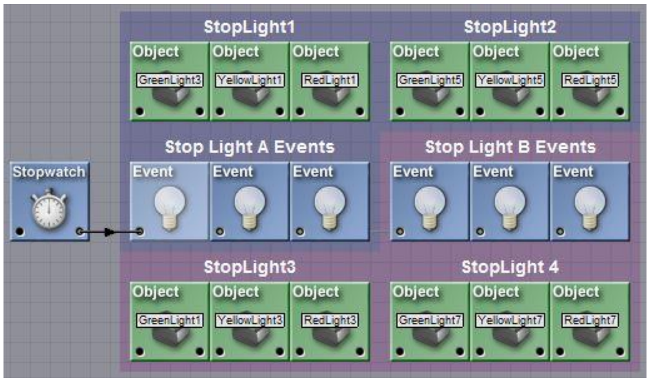


Figure 43 Modules Used for Stop Lights

To determine if a user runs a red light, hidden objects were placed at the intersections and collisions were detected between the camera and the hidden objects. The modules used for determining if the driver ran a red light are shown in Figure 44. Collisions were only detected if the red light event for that intersection was true. A counter module keeps track of how many times the driver ran a red light and was displayed to the driver. Similarly to the highway scene, the colors of the scene change colors and a hitting sound is heard when a driver runs a red light.

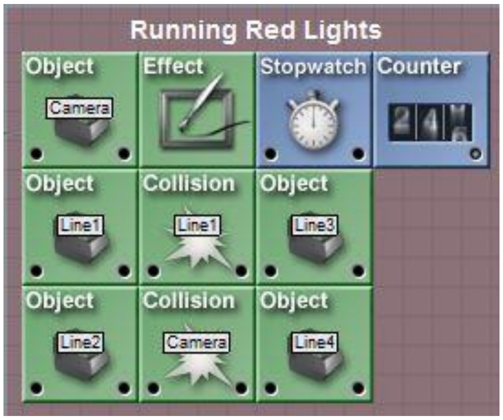


Figure 44 Modules Used for Running Red Lights

## CHAPTER 6: METHODS

Testing included two parts of human subject data collection and a system test. The aim of the human subject data collection was to obtain feedback about the system and to generate improvements that could be made. The aim of the system test was to analyze how the system was performing.

### 6.1 Subjects

In order to obtain feedback about the system, human subject testing was performed (IRB approval #20455, Appendix D). The study consisted of 10 able-bodied participants. The sample had six males and four females whose ages were between 21 and 29. Each subject gave informed consent prior to testing, had a valid driver's license, drives on a normal basis, and does not use adaptive driving controls.

### 6.2 Data Collection Procedures

The driving simulator was set up on the CAREN system following standard operating procedures (Appendix G). These procedures include using ratchet straps to secure the table and wheelchair, putting the safety harness on the subject, and securing driving controls to the table.

Once testing was ready to begin, an overview of the system and directions of what to do were described to the subject. The subject then spent a few minutes driving through the simulation without the dynamic feedback in order to get used to it. The subjects then completed six randomized trials as follows:

1. Highway scene, gaming controls, no dynamic feedback
2. Highway scene, gaming controls, dynamic feedback

3. Highway scene, adaptive controls, dynamic feedback
4. City scene, gaming controls, no dynamic feedback
5. City scene, gaming controls, dynamic feedback
6. City scene, adaptive controls, dynamic feedback

For the highway scene, subjects were instructed to accelerate to 70 mph and then maintain that speed while avoiding other cars and staying in the lanes of the road. After a few minutes, the subjects were told to decelerate to a stop. For the city scene, subjects were instructed to follow the rules of the road by staying in the appropriate lane and not running red lights or stop signs. Subjects were told that the speed limit was 25 mph.

After each trial that contained motion feedback, subjects completed a survey which consisted of a rating and questionnaire. The survey was brought to the subject so the subject was able to stay seated while completing it. After all of the trials were complete, subjects completed one final post-survey regarding the system in general. These two surveys can be found in Appendix E.

The rating portion of the survey consisted of the following questions which were rated on a 1-5 scale:

1. Was the driving simulator motion smooth or jerky? (1=extremely smooth, 2=fairly smooth, 3=neutral, 4=fairly jerky, 5=extremely jerky)
2. How was the realism? (1=very real, 2=somewhat real, 3=neutral, 4=not very real, 5=not real at all)
3. How would you rate the amount of forwards and backwards movement? (1=did not feel any motion, 2=not enough motion, 3=a perfect amount of motion, 4=a little too much motion, 5=way too much motion)

4. How would you rate the amount of side to side movement? (1=did not feel any motion, 2=not enough motion, 3=a perfect amount of motion, 4=a little too much motion, 5=way too much motion)
5. Did you experience any motion sickness? (1=no motion sickness, 2=slight discomfort, 3=dizziness, 4=nausea, 5=vomiting)
6. How would you rate the gas pedal sensitivity? That is, how fast/slow you pass through the visual scene when you press the gas pedal. (1=way too much, 2=too much, 3=just right, 4=too little, 5=way too little)
7. How would you rate the brake pedal sensitivity? That is, how fast/slow you come to a stop when you press the brake pedal. (1=way too much, 2=too much, 3=just right, 4=too little, 5=way too little)
8. How would you rate the steering sensitivity? That is, how much you turn when you turn the steering wheel. (1=way too much, 2=too much, 3=just right, 4=too little, 5=way too little)
9. How would you rate the driving simulator overall? (1=excellent, 2=good, 3=fair, 4=poor, 5=very poor)
10. How would you rate the amount of acceleration felt? (1=way too much, 2=too much, 3=just right, 4=too little, 5=way too little)
11. How would you rate the timing of the acceleration felt? (1=very delayed, 2=a little delayed, 3=just right, 4=too soon, 5=way too soon)

These questions were created in order to find areas of the simulation that need to be adjusted such as the platform filter parameters, steering sensitivity, gas pedal sensitivity, and brake sensitivity.

Additional free response questions gave subjects the chance to describe their experience and give their thoughts on the quality of the simulator and ideas for improvement:

- Did the acceleration that you felt match the visual display on the screen?
- Were there any distracting motion sensations?
- Did the motion have a positive effect on the simulation?
- How was driving with the controls? Was it easy to learn?
- Do you have any suggestions for improvement?
- Any other comments?

The post-survey was set up similarly to the motion trial survey with both ratings and a questionnaire. The post-survey was intended to assess the driving simulator overall. The rating portion consisted of the following questions:

1. How would you rate the virtual environments? (1=excellent, 2=good, 3=fair, 4=poor, 5=very poor)
2. How would you rate the driving set-up? (1=excellent, 2=good, 3=fair, 4=poor, 5=very poor)
3. How would you rate the driving simulator overall? (1=excellent, 2=good, 3=fair, 4=poor, 5=very poor)

The questionnaire portion included the following free response questions:

- Which scene did you drive better in? Which scene was more realistic? Which scene was more fun?
- How was driving with the gaming controls? Was it easy to learn?
- How was driving with the adaptive controls? Was it easy to learn?
- Was it better driving with motion or without motion?
- Do you have any suggestions for improvement?
- Any other comments?

Data collection was split up into two parts. Part one involved the first five subjects testing the system as is. After the first five subjects completed a data collection, improvements were made to the simulator based on the feedback that was obtained. Part two involved the final five subjects testing the system with the new improvements. The results from the final five subjects showed how those changes improved the system.

To show how the subjects rated the simulator collectively, the average and standard deviation of the rating results were calculated. Also, the questionnaire results were summarized and a list of improvements were made. This process was repeated for part one and part two of the data collection.

### 6.3 System Test

A system test was conducted for a specified scenario in order to observe how the system performs. The scenario was to:

1. Accelerate
2. Decelerate
3. Make a right turn

4. Decelerate to a stop

Collected data included driving control inputs, visual accelerations, platform accelerations, visual velocities, and platform positions. Graphs from the collected data were created and analyzed.

# CHAPTER 7: RESULTS AND DISCUSSION

## 7.1 Part One

The average and standard deviation of the rating results for part one of the data collection, which includes the first five subjects, are shown in Table 5 and 6. The complete results are shown in Appendix F.

Table 5 Average and S.D. of Rating Results for Dynamic Trials Part One

| **QUESTION** | | | | | **Highway, Game** | **Highway, Adaptive** | **City, Game** | **City, Adaptive** |
|---|---|---|---|---|---|---|---|---|
| Was the driving simulator motion smooth or jerky? | | | | | 1.6±0.5 | 2.2±0.4 | 2.8±1.5 | 2.2±1.0 |
| 1. Extremely Smooth | 2. Fairly Smooth | 3. Neutral | 4. Fairly Jerky | 5. Extremely Jerky | | | | |
| How was the realism? | | | | | 2.2±1.2 | 2.2±0.4 | 2.2±0.7 | 2.2±0.7 |
| 1. Very real | 2. Somewhat real | 3. Neutral | 4. Not very real | 5. Not real at all | | | | |
| How would you rate the amount of forward and backwards movement? | | | | | 3±0.6 | 2.8±0.4 | 3±0 | 2.8±0.4 |
| 1. Did not feel any motion | 2. Not enough motion | 3. A perfect amount of motion | 4. A little too much motion | 5. Way too much motion | | | | |
| How would you rate the amount of side to side movement? | | | | | 3±0 | 3±0.6 | 3.2±0.4 | 2.8±0.4 |
| 1. Did not feel any motion | 2. Not enough motion | 3. A perfect amount of motion | 4. A little too much motion | 5. Way too much motion | | | | |
| Did you experience any motion sickness? | | | | | 1.4±0.8 | 1.4±0.5 | 1.8±1.2 | 1.2±0.4 |
| 1. No motion sickness | 2. Slight Discomfort | 3. Dizziness | 4. Nausea | 5. Vomiting | | | | |

Table 5 (Continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| How would you rate the gas pedal sensitivity? That is, how fast/slow you pass through the visual scene when you press the gas pedal. | | | | | 3.2±0.4 | 3.2±0.4 | 2.8±0.4 | 2.8±0.4 |
| 1.Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the brake pedal sensitivity? That is, how fast/slow you come to a stop when you press the brake pedal. | | | | | 3.6±0.5 | 3.4±0.5 | 3.6±0.5 | 3.2±0.7 |
| 1.Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the steering sensitivity? That is, how much you turn when you turn the steering wheel. | | | | | 3±0 | 2.6±0.5 | 2.2±0.7 | 3.6±1.4 |
| 1. Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the driving simulator overall? | | | | | 2±0.6 | 2.2±0.7 | 2.2±0.7 | 2.0±0.6 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | | | | |
| How would you rate the amount of acceleration felt? | | | | | 3.4±0.5 | 3.4±0.5 | 3.2±0.4 | 3.2±0.4 |
| 1.Too much | 2. A little too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the timing of the acceleration felt? | | | | | 2.4±0.5 | 2.8±0.4 | 3.2±0.4 | 3.0±0 |
| 1.Very delayed | 2. A little delayed | 3. Just right | 4. Too soon | 5. Way too soon | | | | |

Table 6 Average and S.D. of Rating Results for Post-Survey Part One

| **QUESTION** | | | | | **Post-Survey** |
|---|---|---|---|---|---|
| How would you rate the virtual environments? | | | | | 2.0±0.6 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | |
| How would you rate the driving set-up? | | | | | 1.8±0.4 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | |

Table 6 (Continued)

| How would you rate the driving simulator overall? | | | | | 2.0±0.6 |
|---|---|---|---|---|---|
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | |

Looking at the rating results, subjects described that the simulator motion was more smooth than jerky and that it was somewhat real. Subjects also described that there was a perfect amount of motion. Three subjects did not experience any motion sickness. One subject had slight discomfort and another experienced dizziness and nausea. It was observed that the two subjects that experienced motion sickness drove faster and rougher than the other three subjects. Most subjects mentioned in the surveys that the brake pedal sensitivity was not enough and the feeling of braking was not there. Rating results show that the brake pedal sensitivity was in between bring just right and too little. Subjects had a difficult time driving with the adaptive steering control but mentioned in the surveys that they eventually got used to it. They felt that it took too many revolutions to make a small steering change and that they never really knew where the center was. Subjects had an easier time with the gaming controls but thought that the steering sensitivity was too much in the city scene. Subjects thought that the amount of acceleration was not enough and that the acceleration sometimes felt delayed. Overall, subjects thought that the accelerations felt matched what was displayed and only one subject mentioned the false cue of the platform coming to the center after coming to a stop. Survey comments related to the virtual environment include speeding up the cars on the highway and lowering the speed display. All subjects except for one accidentally moved the gaming pedals in the middle of data collection causing subjects to collide with other cars and to run red lights. Post-survey results gave the virtual environments, the driving set-up, and the simulator overall a rating of ‘good’.

Improvement ideas gathered from part one are listed below and was implemented before collecting data for part two:

- *Adaptive Steering Change:* Steering was programmed using a variable steering constant to avoid over steering when the wheel is near the center and to avoid under steering when turning maneuvers are being done. This concept works using the gaming steering wheel because the driver knows where the center position is since the steering wheel naturally comes back to the center when it is let go. The adaptive steering wheel, on the other hand, does not automatically come back to the center and includes many revolutions. Because subjects did not know where the steering wheel position was, they would transition from less sensitivity to more sensitivity and have a difficult time getting the car under control. To fix this, the adaptive steering will have a constant steering constant for part two so that the sensitivity will be the same no matter what position the steering wheel is in.
- *Speed up highway cars:* Subjects mentioned that the highway cars drove too slowly relative to their speed. In part two, the highway cars will drive at a speed closer to the driver's speed.
- *Lower speed display:* Subjects felt like they had to constantly look up to see what their speed was. By lowering the speed display, subjects can have an easier time glancing between the road and the speed display.
- *Mount pedals:* Four out of the five subjects accidentally knocked the pedals away from them. To keep the lightweight pedals in place, weight was placed behind the pedals so they cannot easily be moved.
- *Increase brake sensitivity:* The brake sensitivity will be increased to better simulate the feeling of braking.

- *Decrease gaming steering sensitivity slope:* Subjects thought that the gaming steering sensitivity was just right in the highway scene but too much in the city scene. This is because of the slope of the variable steering constant. By decreasing the slope, sensitivity can be decreased in the city scene where turning maneuvers are done but kept the same in the highway scene.

### 7.2 Part Two

The average and standard deviation of the rating results for part two of the data collection, which includes the last five subjects, are shown in Table 7 and 8. The complete results are shown in Appendix F. It should be noted that one subject experienced motion sickness after completing the first trial and survey (city environment with game controls) and could not continue the data collection.

Table 7 Average and S.D. of Rating Results for Dynamic Trials Part Two

| **QUESTION** | | | | | **Highway, Game** | **Highway, Adaptive** | **City, Game** | **City, Adaptive** |
|---|---|---|---|---|---|---|---|---|
| Was the driving simulator motion smooth or jerky? | | | | | 1.3±0.4 | 2.3±0.8 | 2.6±1.2 | 1.8±0.8 |
| 1. Extremely Smooth | 2. Fairly Smooth | 3. Neutral | 4. Fairly Jerky | 5. Extremely Jerky | | | | |
| How was the realism? | | | | | 1.8±0.4 | 2.0±0.7 | 2.0±0.6 | 1.8±0.4 |
| 1. Very real | 2. Somewhat real | 3. Neutral | 4. Not very real | 5. Not real at all | | | | |
| How would you rate the amount of forward and backwards movement? | | | | | 2.8±0.4 | 2.5±0.5 | 2.4±0.8 | 2.5±0.5 |
| 1. Did not feel any motion | 2. Not enough motion | 3. A perfect amount of motion | 4. A little too much motion | 5. Way too much motion | | | | |
| How would you rate the amount of side to side movement? | | | | | 2.8±0.4 | 2.5±0.5 | 3.2±0.7 | 2.8±0.4 |
| 1. Did not feel any motion | 2. Not enough motion | 3. A perfect amount of motion | 4. A little too much motion | 5. Way too much motion | | | | |

Table 7 (Continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Did you experience any motion sickness? | | | | | 1.0±0.0 | 1.0±0.0 | 1.6±0.8 | 1.0±0.0 |
| 1. No motion sickness | 2. Slight Discomfort | 3. Dizziness | 4. Nausea | 5. Vomiting | | | | |
| How would you rate the gas pedal sensitivity? That is, how fast/slow you pass through the visual scene when you press the gas pedal. | | | | | 3.0±0.7 | 3.0±0.0 | 2.8±0.4 | 3.0±0.0 |
| 1.Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the brake pedal sensitivity? That is, how fast/slow you come to a stop when you press the brake pedal. | | | | | 3.3±0.4 | 3.3±0.4 | 3.0±0.6 | 3.0±0.0 |
| 1.Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the steering sensitivity? That is, how much you turn when you turn the steering wheel. | | | | | 3.0±0.0 | 2.0±0.0 | 2.6±0.5 | 3.5±1.7 |
| 1. Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the driving simulator overall? | | | | | 1.5±0.5 | 1.8±0.4 | 1.8±0.4 | 2.0±0.0 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | | | | |
| How would you rate the amount of acceleration felt? | | | | | 3.3±0.4 | 3.3±0.4 | 3.2±0.4 | 3.3±0.4 |
| 1.Too much | 2. A little too much | 3. Just right | 4. Too little | 5. Way too little | | | | |
| How would you rate the timing of the acceleration felt? | | | | | 3.0±0.0 | 3.0±0.0 | 3.0±0.0 | 3.0±0.0 |
| 1.Very delayed | 2. A little delayed | 3. Just right | 4. Too soon | 5. Way too soon | | | | |

Table 8 Average and S.D. of Rating Results for Post-Survey Part Two

| **QUESTION** | | | | | **Post-Survey** |
|---|---|---|---|---|---|
| How would you rate the virtual environments? | | | | | 2.0±0.0 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | |

Table 8 (Continued)

| | | | | | |
|---|---|---|---|---|---|
| How would you rate the driving set-up? | | | | | 1.3±0.4 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | |
| How would you rate the driving simulator overall? | | | | | 1.5±0.5 |
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor | |

One difference between part one and part two is that the overall ratings improved slightly in part two. Subjects also rated the brake sensitivity to be just right, compared with being too little in part one. Nobody mentioned anything about the cars on the highway, speed display, or knocked the pedals out of the way. In addition, the steering sensitivity for the gaming controls in the city scene improved from 2.2 to 2.6. Even though subjects still voiced that they had a difficult time using the adaptive controls, they were observed to take less time getting acclimated to the controls during their practice session. These differences show that the changes that were implemented improved the simulator.

From the ratings and questionnaires, additional enhancements that could be implemented in the future are listed below:

- *Acceleration:* Ratings from part one and part two show that the amount of acceleration felt and the amount of movement was slightly too little. The motion cueing variables, such as high pass filter parameters, low pass filter parameters, and gains, should be adjusted in order to feel more acceleration.
- *Steering sensitivities:* The steering sensitivities, especially for the adaptive controls, should be experimented with to find the optimal values.
- *Different controls:* Subjects mentioned that, while the gaming controls did closely mimic real car controls, they were slightly different. Subjects said that a real car steering wheel

goes back to the center more smoothly than the gaming controls did. Also, the adaptive controls were difficult to use because the center position was not known. Different control options should be experimented with, such a joystick option, different gaming controls, and mechanical adaptive controls.

- *Mirrors:* Mirrors could be used in order to see if drivers have passed a car or to look behind. This will most likely be a challenge since D-Flow only allows for one camera module.

### 7.3 System Test

Figures 45 through 50 display the results from the system test. Figure 45 shows the inputs from the gas and steering. For the gas input, a positive value corresponds to using the gas and a negative value corresponds to using the brake. For the steering input, a positive value corresponds to turning the steering wheel to the left and a negative value corresponds to turning the steering wheel to the right. From Figure 45, it can be seen that there was an input from the gas between 0 and 10 seconds. Between 10 and 15 seconds and between 20 and 25 seconds, the brake was used. Between 15 and 20 seconds, the steering wheel was turned to the right.

Figure 46 displays the visual longitudinal speed and visual angular speed. The longitudinal speed increased to 40 miles per hour between 0 and 10 seconds and then decreased back to 0 afterwards. Between 15 and 20 seconds, the angular speed was negative, corresponding to turning right. From the combination of Figure 45 and 46, it can be seen that the system test scenario discussed in Section 6.3 was followed correctly. First, an acceleration was made followed by a deceleration. Then, a right turn was made. Finally, a stop was completed.

Figures 47 and 48 compare the visual accelerations seen on the projection screen with the platform accelerations. Longitudinal acceleration consisted of a surge and pitch platform movement whereas centripetal acceleration consisted of a sway and roll platform movement.

Figures 49 and 50 show the platform positions. It should be noted that the limits for the surge and sway platform positions are between -0.22 and 0.22 meters and the limits for the pitch and roll platform positions are between -18 and 18 degrees.

Looking at the surge movement, there was a spike in acceleration values every time there was a change in gas input (Figure 47). These spikes are the initial cues. The sway movement showed a similar spike in acceleration representing an initial cue when the right turn was made (Figure 48).

A positive surge position corresponds to the platform moving forwards and a negative surge position corresponds to the platform moving backwards. From Figure 49, it can be seen that the platform moved forward when there was an acceleration and moved backwards when there was a deceleration. A false cue inherent in the motion cueing algorithm is seen when the platform position continues to move forward after the visual speed goes to zero.

A positive sway position corresponds to the platform moving to the right and a negative sway position corresponds to the platform moving to the left. When a right turn was made, the platform swayed to the left, giving the feeling of being pushed outward when turning.

Figures 47 and 48 show that the roll and pitch accelerations were delayed. This is due to the rate limiting algorithm. Future work should include testing with higher rate limits in order to reduce the delay seen. Nonetheless, the roll and pitch provided sustained acceleration cues after the initial cues ended.

It is shown that the platform accelerations were smaller than the visual accelerations. This is because the visual accelerations were scaled down in order to stay within the platform bounds. Figures 49 and 50 show that the platform did, in fact, stay within its bounds. This gives enough room to adjust the filter parameters in the future in order to feel more acceleration.

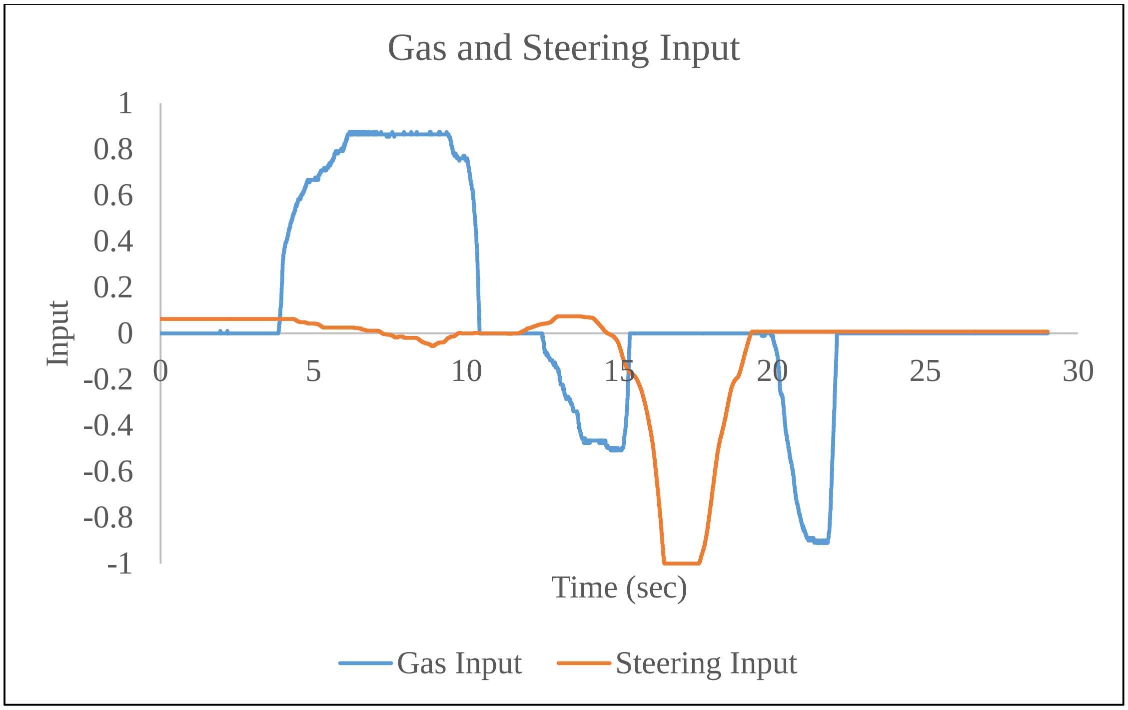


Figure 45 Gas and Steering Input

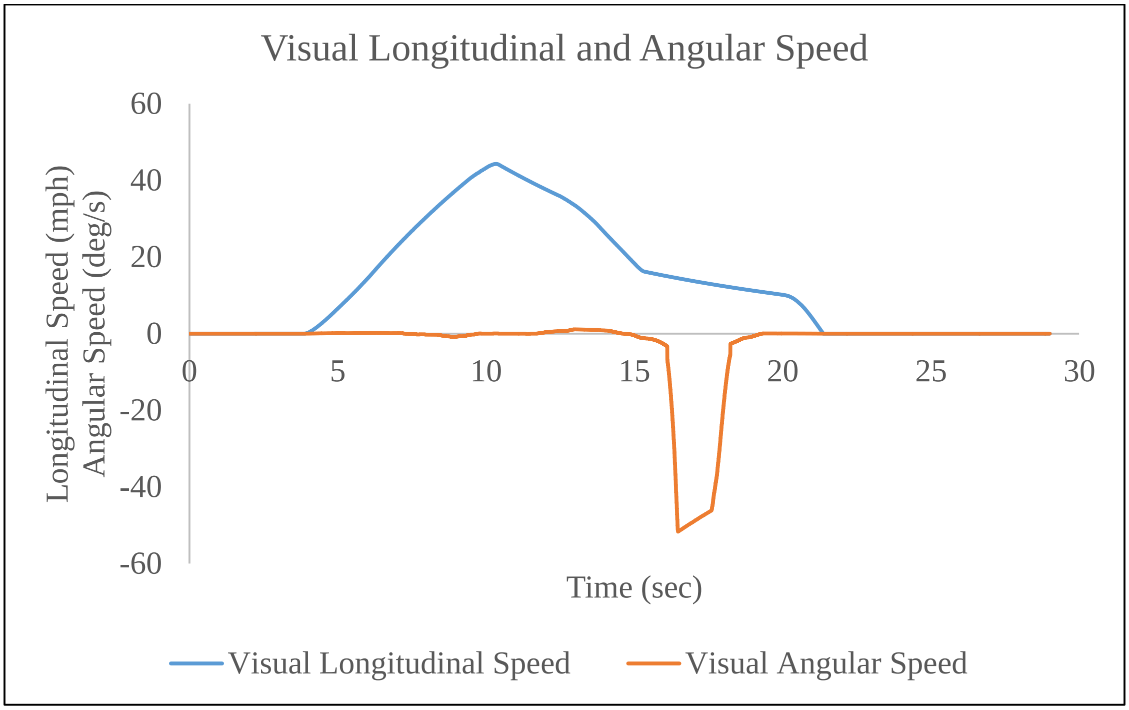


Figure 46 Visual Longitudinal and Angular Speed

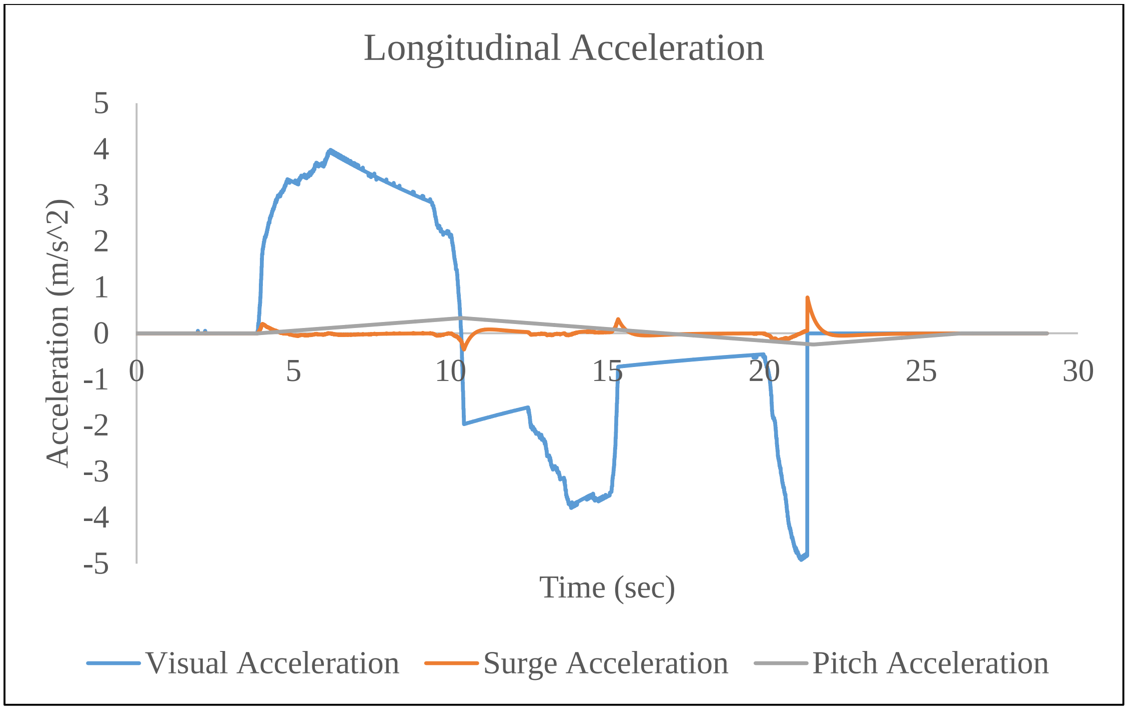


Figure 47 Longitudinal Acceleration

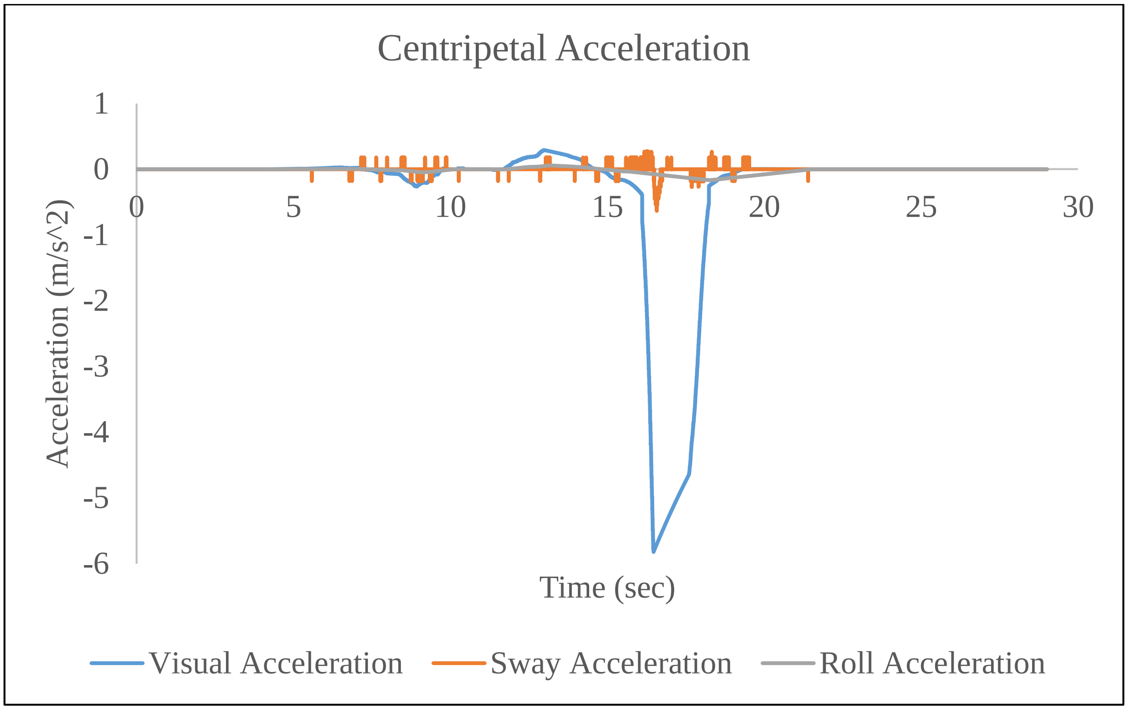


Figure 48 Centripetal Acceleration

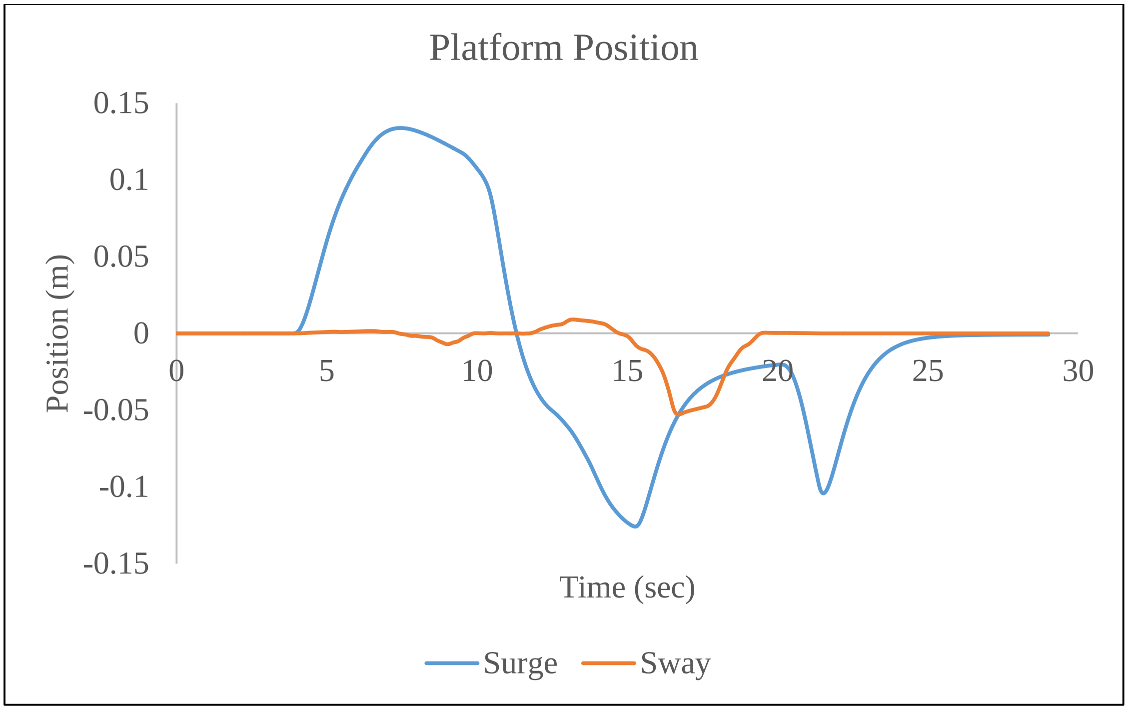


Figure 49 Platform Position

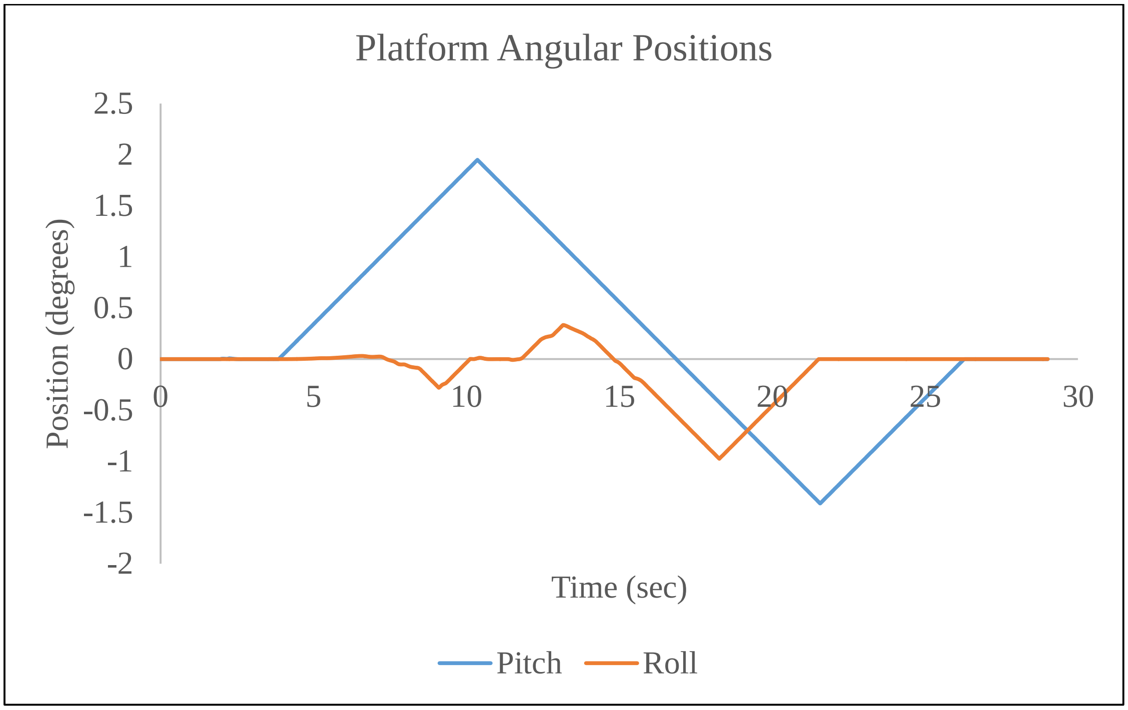


Figure 50 Platform Angular Positions

### 7.4 Limitations

One limitation of this study was the CAREN system. The CAREN system has other rehabilitation applications to it besides driving simulation, so the simulator had to be developed from the ground up using the system's D-Flow programming environment. The idea was to adapt the CAREN for driving simulation in order to be used in the future as part of a more inclusive rehabilitation program, not driving simulation alone. The scene development using Google Sketchup was another limitation related to the CAREN system. Using a different modeling software other than Google Sketchup could provide better graphics and modeling capability.

Another limitation was using older adaptive controls. There are many newer models of adaptive controls available. Additionally, this study only looked at one type of adaptive control, the gas/brake lever and reduced effort steering wheel combination. Subjects were not able to choose which type of adaptive control they prefer because other devices, such as the joystick, were not used.

A limitation related to testing was the number of subjects. With more subjects, more feedback and improvements could have been made. Nonetheless, testing showed that the driving simulator created was realistic and the motion felt similar to accelerations felt from driving a real car.

Another limitation was not testing with SCI subjects. Testing with SCI subjects could lead to valuable feedback especially if they have experience driving with adaptive controls. This can allow for comparison against real adaptive driving systems. Also, it was not tested to see if dynamic movement affects their driving ability. The dynamic movement could lead to an increase in torso movement which could cause fatigue and a loss of control.  This, in turn, could negatively impact their driving performance. This study only looked at qualitative data from human subject testing through the use of surveys. It did not collect quantitative data such as torso movement or driving performance measures and should be addressed in the future.

.

# CHAPTER 8: CONCLUSIONS

## 8.1 Conclusions

In this study, a driving simulator was created using the CAREN system. The driving simulator provided visual feedback through the system's projection screen as well as dynamic feedback through the system's motion platform. This feedback was programmed to perform similar to a real car.  Input to the system came from either gaming controls, which mimicked controls found in a real car, or adaptive DBW controls, which are used in vehicle modifications for individuals with SCI. The virtual camera view movement was controlled using input signals from these driving controls. Basic equations were used that aimed to make the virtual camera move like a real car would. These equations created virtual accelerations in the longitudinal and centripetal directions. Motion cueing theory was used that translated these visual accelerations to dynamic accelerations of the motion platform. A highway and city scene were created and incorporated into the driving environment. Initial testing was done with five healthy individuals in order to evaluate the realism of the simulator and to obtain some improvements that can be integrated into the simulator. After implementing those changes, testing was repeated with five additional subjects and the results showed that those changes did improve the simulator. A system test was conducted that showed that the simulator behaved like was expected.

This thesis contributes to research by developing a dynamic driving simulator aimed for individuals with SCI. Most driving simulators for individuals with SCI do not incorporate motion feedback and use mechanical hand controls. The simulator developed incorporates dynamic feedback and uses electrical hand controls. This simulator is a platform for future research in driving training and performance in individuals with SCI.

This research has shown that the CAREN system can be used successfully as a platform for driving simulation, in addition to other rehabilitation applications. With future work, it can be used to train and evaluate individuals with SCI who are learning how to drive, which will greatly improve their quality of life.

## 8.2 Future Work

This study was a starting point for driving simulation using the CAREN system. Future work should include addressing the limitations of this study in order to achieve the ultimate goal of training and evaluating individuals with SCI.

To improve the simulator realism, graphics could be developed using more advanced modeling software. New environments, a car dashboard, and pedestrians are examples of graphics that could be developed. Basic geometry and physics was used to model the camera movement in this thesis. In the future, the camera movement algorithm could incorporate more advanced motion dynamics such as changing gears and road friction. Optimizing the platform movement would involve changing the various filtering parameters and having subjects rate how they like the changes in a trial and error process. The parameters that could be changed include high pass filtering parameters, low pass filtering parameters, and tilt coordination parameters.

Once the simulator is optimized, research can be done to test driving performance in individuals with SCI. Testing should be done with and without the dynamic feedback to look at how the dynamic movement affects torso movement. Too much torso movement could lead to driver fatigue and is a measure of driver control, which is an important factor in SCI. Torso movement can easily be measured using CAREN's motion capture system. Additionally, driving performance can be measured during a driving session by recording quantitative items such as speed variance, steering variance, number of collisions, and reaction time. Different adaptive controls, like joystick devices, should also be incorporated into the system in the future. By testing different controls on the simulator, individuals with SCI can choose which devices they prefer before modifying their own vehicle.

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# APPENDICES

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**Sarah Tudor** <smtudor@mail.usf.edu> Fri, Jan 9, 2015 at 6:32 PM
To: enqs@spinal-injury.net

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I am from University of South Florida and I am writing a thesis on the development of a dynamic driving simulator that will hopefully be used for training individuals with spinal cord injury learn how to drive.

I wanted to use the image of a spine (http://www.spinal-injury.net/spinal-injury-network/images/spine.jpg) that you have on your website in my background section about spinal cord injuries. I just wanted to see if that is okay because I saw in your FAQ that you would like to know before using any material.

Thanks,
Sarah Tudor

**Spinal Injury Net** <enqs@spinal-injury.net> Sat, Jan 10, 2015 at 3:26 AM
To: Sarah Tudor <smtudor@mail.usf.edu>

Hi Sarah

please go ahead with the image

regards

Andy
---------------------------------
www.spinal-injury.net
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**Author:** Gilles Reymond, Andras Kemeny, Jacques Droulez, Alain Berthoz

**Publication:** Human Factors

**Publisher:** SAGE Publications

**Date:** 09/01/2001

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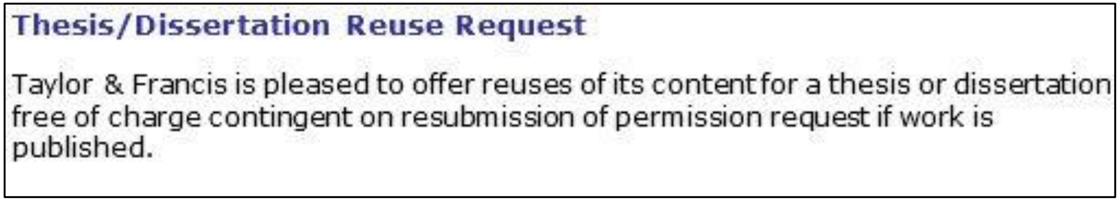

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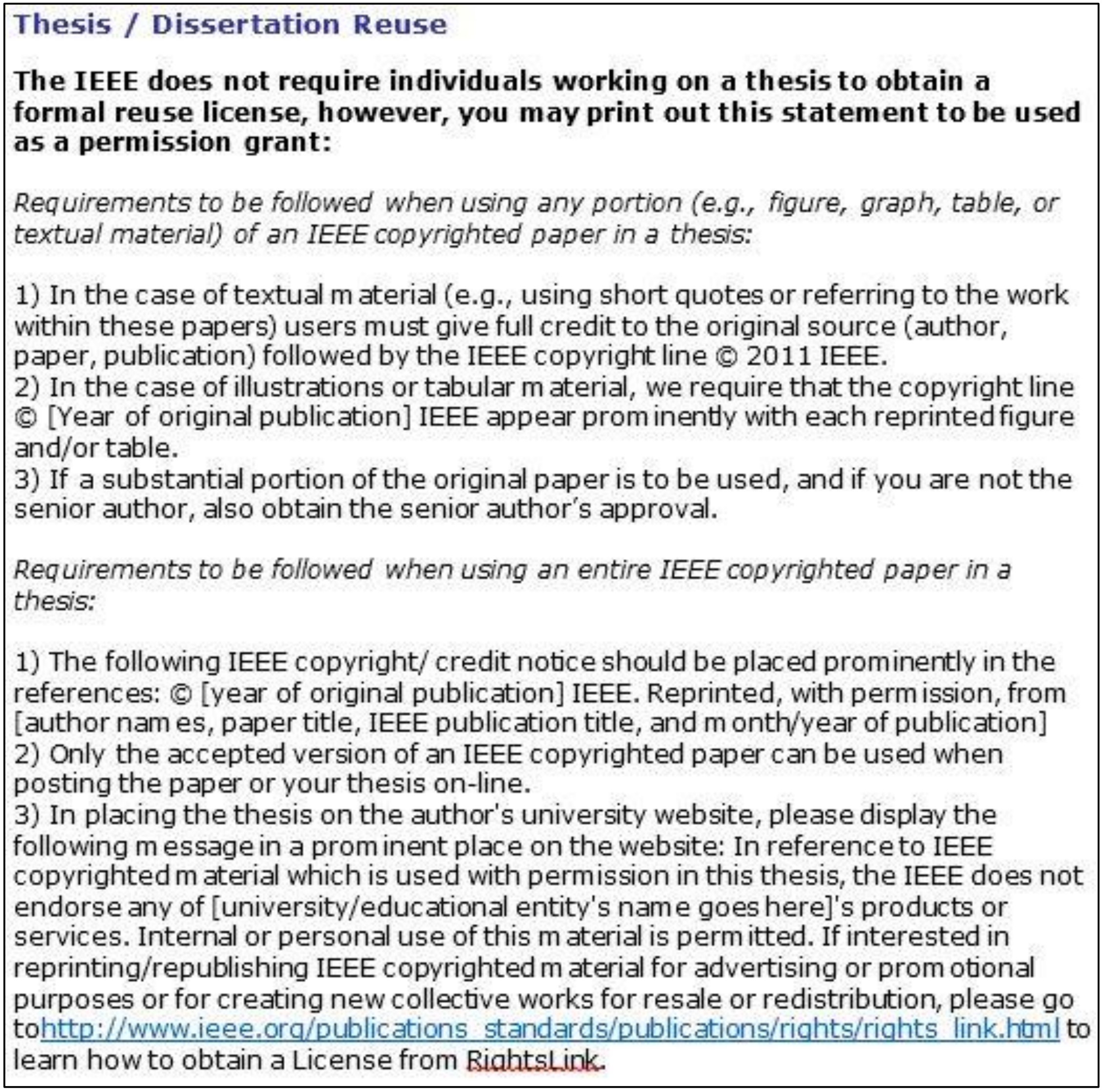

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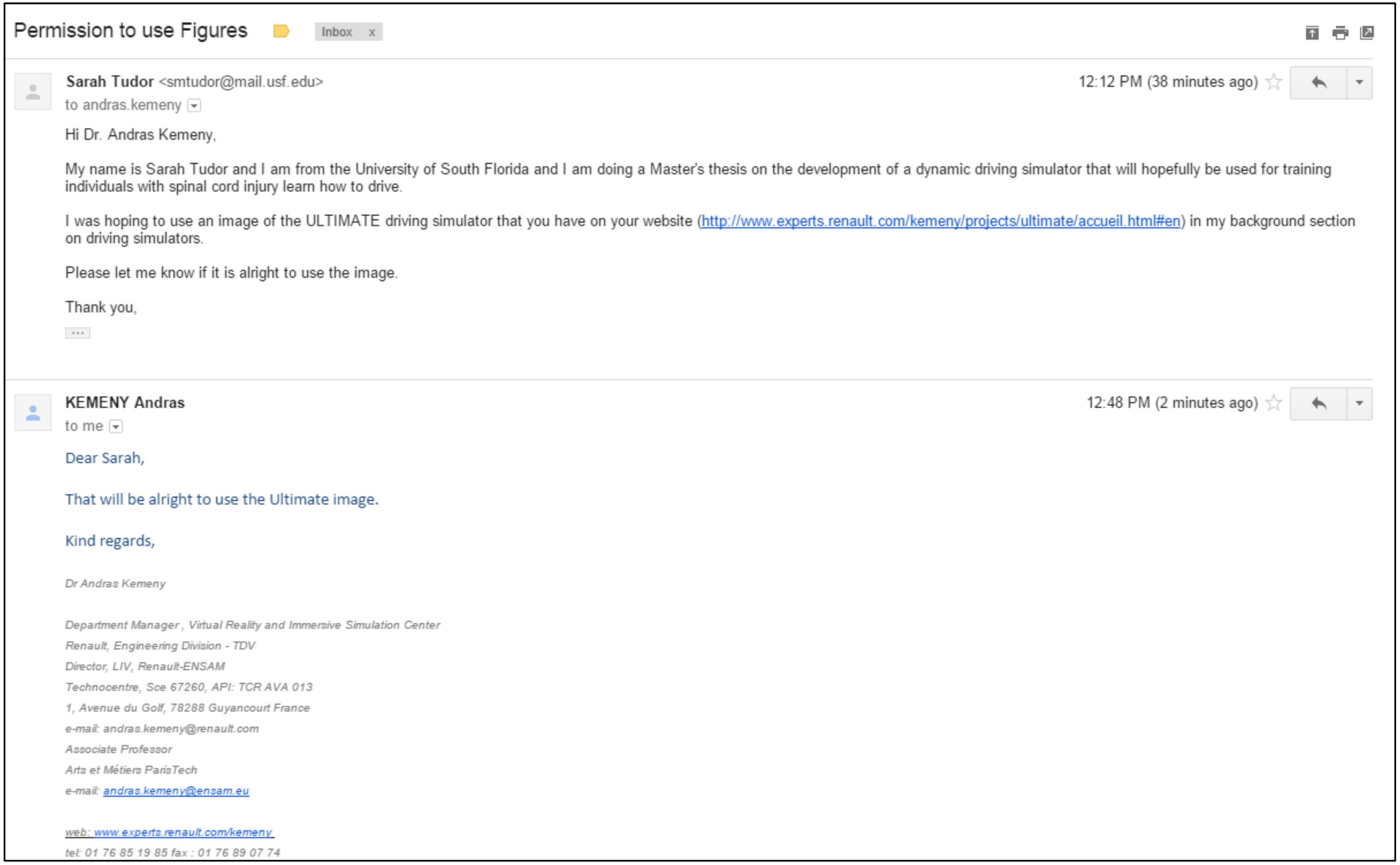

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**Sarah Tudor** <smtudor@mail.usf.edu>
to andras.kemeny

12:12 PM (38 minutes ago)

Hi Dr. Andras Kemeny,

My name is Sarah Tudor and I am from the University of South Florida and I am doing a Master's thesis on the development of a dynamic driving simulator that will hopefully be used for training individuals with spinal cord injury learn how to drive.

I was hoping to use an image of the ULTIMATE driving simulator that you have on your website (http://www.experts.renault.com/kemeny/projects/ultimate/accueil.html#en) in my background section on driving simulators.

Please let me know if it is alright to use the image.

Thank you,

**KEMENY Andras**
to me

12:48 PM (2 minutes ago)

Dear Sarah,

That will be alright to use the Ultimate image.

Kind regards,

*Dr Andras Kemeny*

*Department Manager , Virtual Reality and Immersive Simulation Center*
*Renault, Engineering Division - TDV*
*Director, LIV, Renault-ENSAM*
*Technocentre, Sce 67260, API: TCR AVA 013*
*1, Avenue du Golf, 78288 Guyancourt France*
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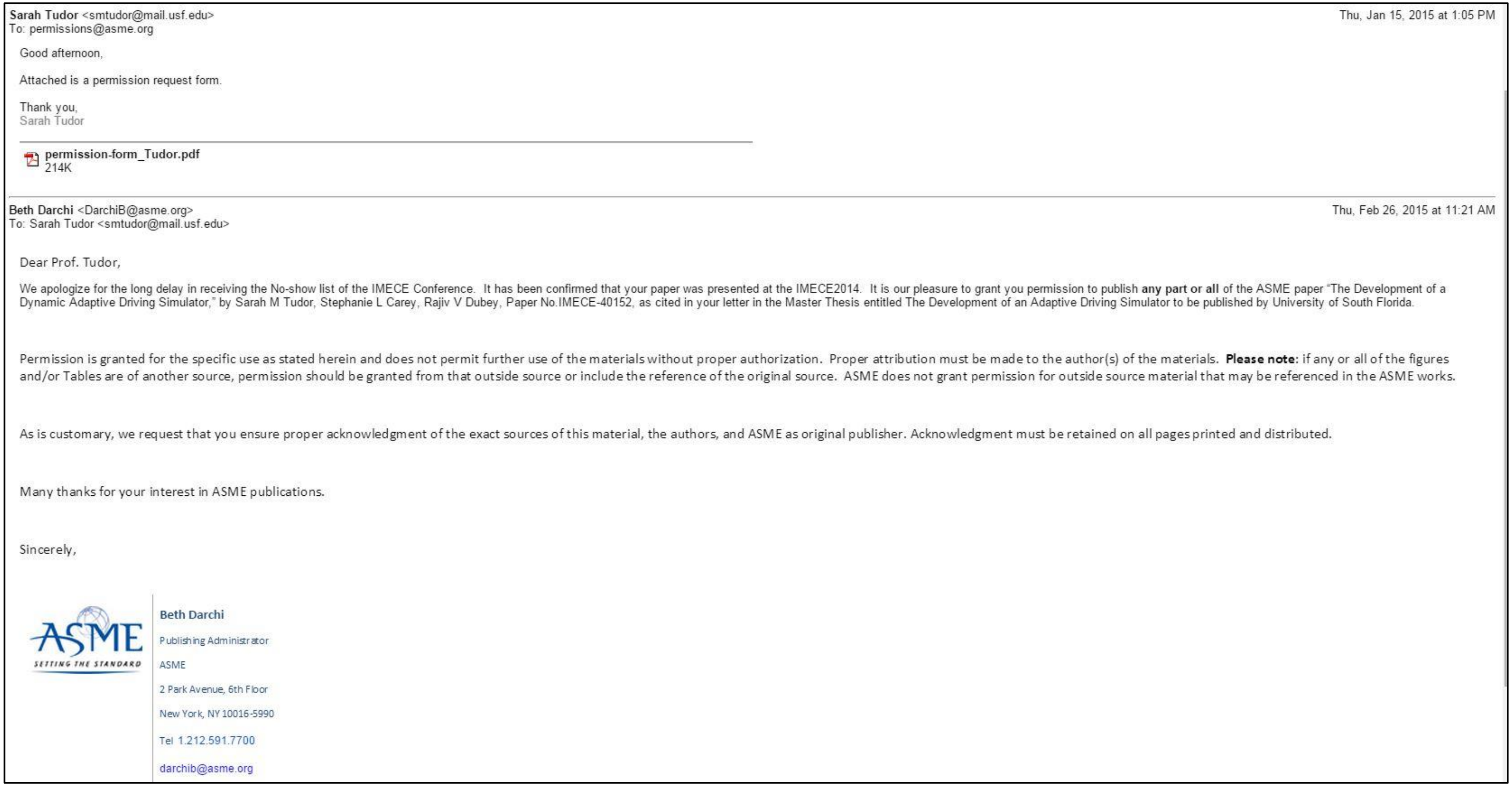

**Sarah Tudor** <smtudor@mail.usf.edu>
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Thu, Jan 15, 2015 at 1:05 PM

Good afternoon,

Attached is a permission request form.

Thank you,
Sarah Tudor

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214K

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**Beth Darchi** <DarchiB@asme.org>
To: Sarah Tudor <smtudor@mail.usf.edu>

Thu, Feb 26, 2015 at 11:21 AM

Dear Prof. Tudor,

We apologize for the long delay in receiving the No-show list of the IMECE Conference. It has been confirmed that your paper was presented at the IMECE2014. It is our pleasure to grant you permission to publish **any part or all** of the ASME paper "The Development of a Dynamic Adaptive Driving Simulator," by Sarah M Tudor, Stephanie L Carey, Rajiv V Dubey, Paper No.IMECE-40152, as cited in your letter in the Master Thesis entitled The Development of an Adaptive Driving Simulator to be published by University of South Florida.

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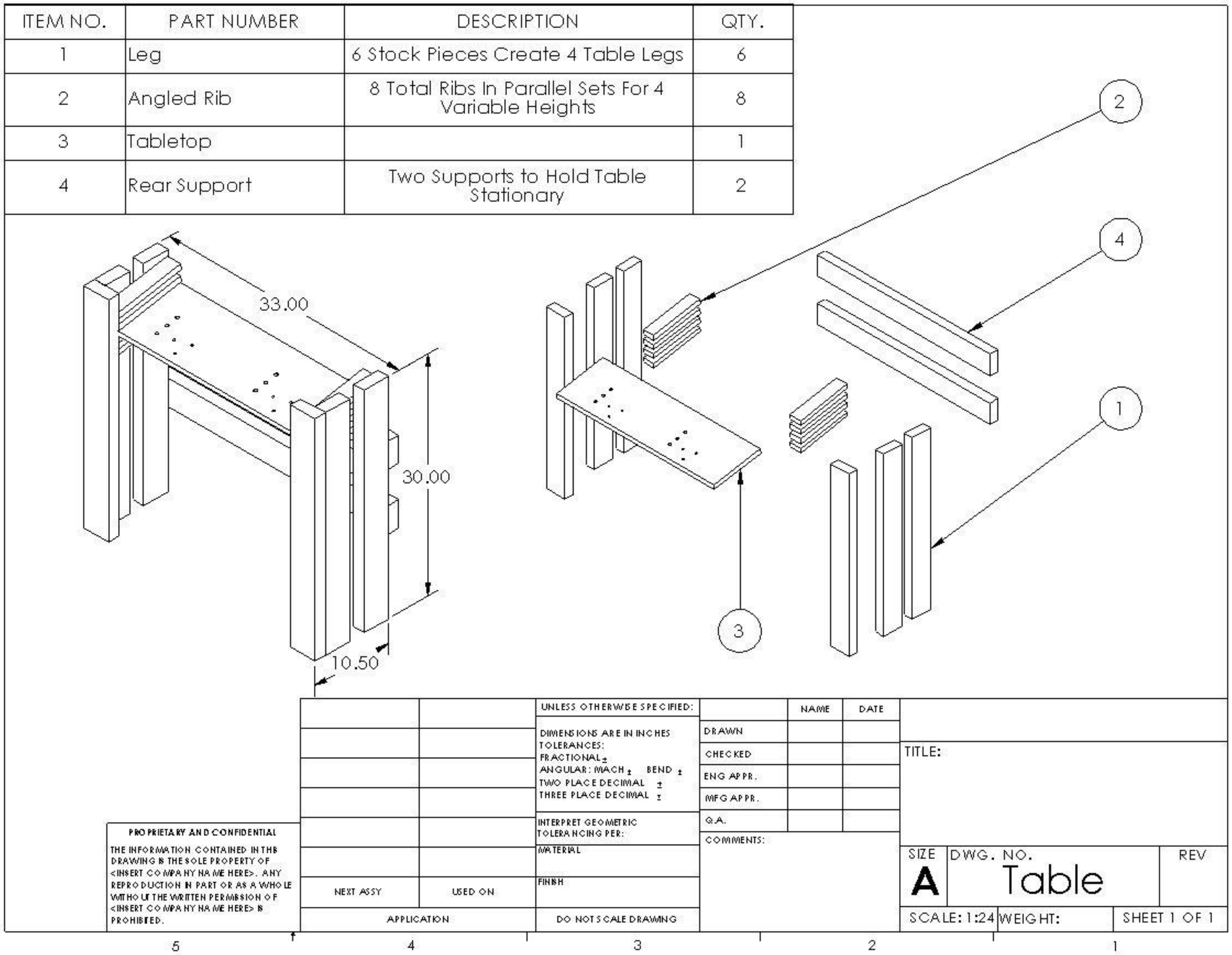
## Appendix B: Table Drawing



| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | Leg | 6 Stock Pieces Create 4 Table Legs | 6 |
| 2 | Angled Rib | 8 Total Ribs In Parallel Sets For 4 Variable Heights | 8 |
| 3 | Tabletop | | 1 |
| 4 | Rear Support | Two Supports to Hold Table Stationary | 2 |

Figure B.1 Table Drawing

## Appendix C: Scripts

### C.1 Camera Movement Script

```
-- Init Variables
init=init or 0

-- Initialization
if init == 0 then
          camera.posX = 0
          camera.posZ = 0
          camera.rotY= 0
          camera.rotX=0
          v = 0
          init = 1
end

--Inputs
Gas_Input=inputs.get(1)
Steering_Input=inputs.get(2)
max_vel=inputs.get(3)
C_s=inputs.get(4)
b=inputs.get(5)
Coll_Car=inputs.get(6)
Dec=inputs.get(7)

--Constants
dt=framedelta()
C_u=b*max_vel/2.237
C_v=Dec*max_vel/2.237
Max_Pitch=math.rad(5)

--Steering
if Steering_Input==0 then
          omega=0
          else
                    if (Steering_Input>0.5) then
                              C_s=(C_s-7)+(14*Steering_Input)
                    elseif (Steering_Input<-0.5) then
                              C_s=(C_s-7)-(14*Steering_Input)
                    end
          omega=v*Steering_Input*C_s
end
camera.rotY=camera.rotY+(omega*dt)

--Gas&Brake
```

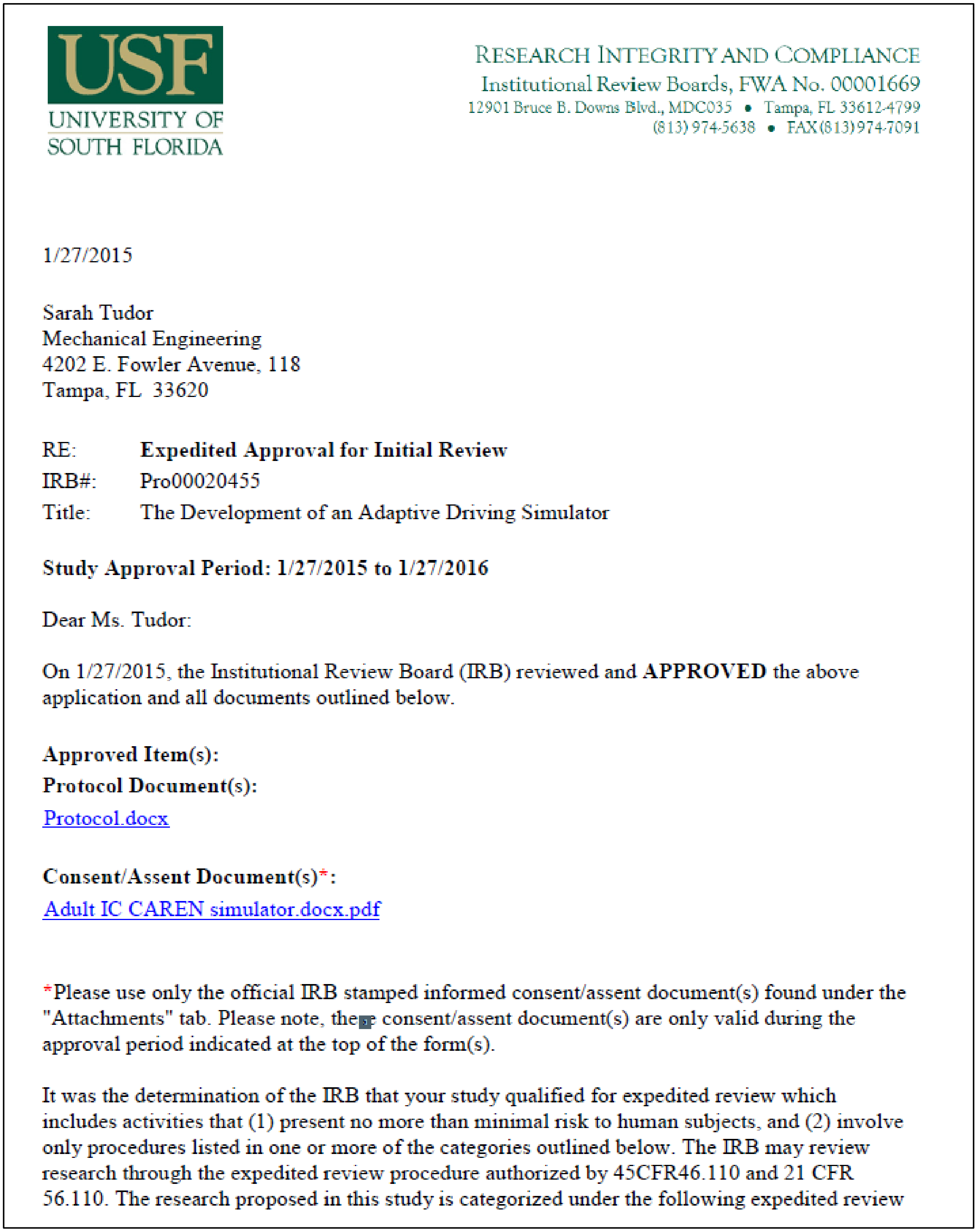
```
if g==1 then
        Gas_Input=0
end
if Gas_Input>0 then
        vdot=(Gas_Input*C_u)-(b*v)
else
        vdot=(Gas_Input*C_v)-(Dec*v)
end

--Velocity
v=v+(vdot*dt)
if v<0 then
        v=0
        vdot=0
end
vel=v*2.237
vx=v*math.sin(math.rad(camera.rotY))
vz=v*math.cos(math.rad(camera.rotY))

--Position
camera.posZ=camera.posZ-(vz*dt)
camera.posX=camera.posX-(vx*dt)

--Centripetal Acceleration
Acent=v*omega*math.pi/180
if Acent>7.5 then
        Acent=7.5
elseif Acent<-7.5 then
        Acent=-7.5
end

--Camera Pitch
if (vel==0) then
        camera.rotX=0
elseif (vdot>=0) then
        camera.rotX=math.deg(Max_Pitch*vdot/C_u)
else
        camera.rotX=math.deg((Max_Pitch*vdot)/(C_v+(Dec*max_vel/2.237)))
end

--Outputs
outputs.set(1,camera.posX)
outputs.set(2,camera.posZ)
outputs.set(3,camera.rotY)
outputs.set(4,camera.rotX)
outputs.set(5,vel)
```

```
outputs.set(6,vdot)
outputs.set(7,omega)
outputs.set(8,Acent)
```

### C.2 Rate Limiting Script

```
init=init or 0

if init == 0 then
        Prev_Theta=0
        init=1
end

dt=framedelta()
Theta = inputs.get(1)

Thetadot = (Theta - Prev_Theta)/dt

if Thetadot>0.3 then
        Theta_out = Prev_Theta + (0.3*dt)
elseif Thetadot>-0.3 then
        Theta_out = Theta
elseif Thetadot<-0.3 then
        Theta_out = Prev_Theta - (0.3*dt)
end
Prev_Theta=Theta_out
outputs.set(1,Theta_out)
```

## Appendix D: IRB Approval



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Mechanical Engineering
4202 E. Fowler Avenue, 118
Tampa, FL 33620

RE: **Expedited Approval for Initial Review**
IRB#: Pro00020455
Title: The Development of an Adaptive Driving Simulator

**Study Approval Period: 1/27/2015 to 1/27/2016**

Dear Ms. Tudor:

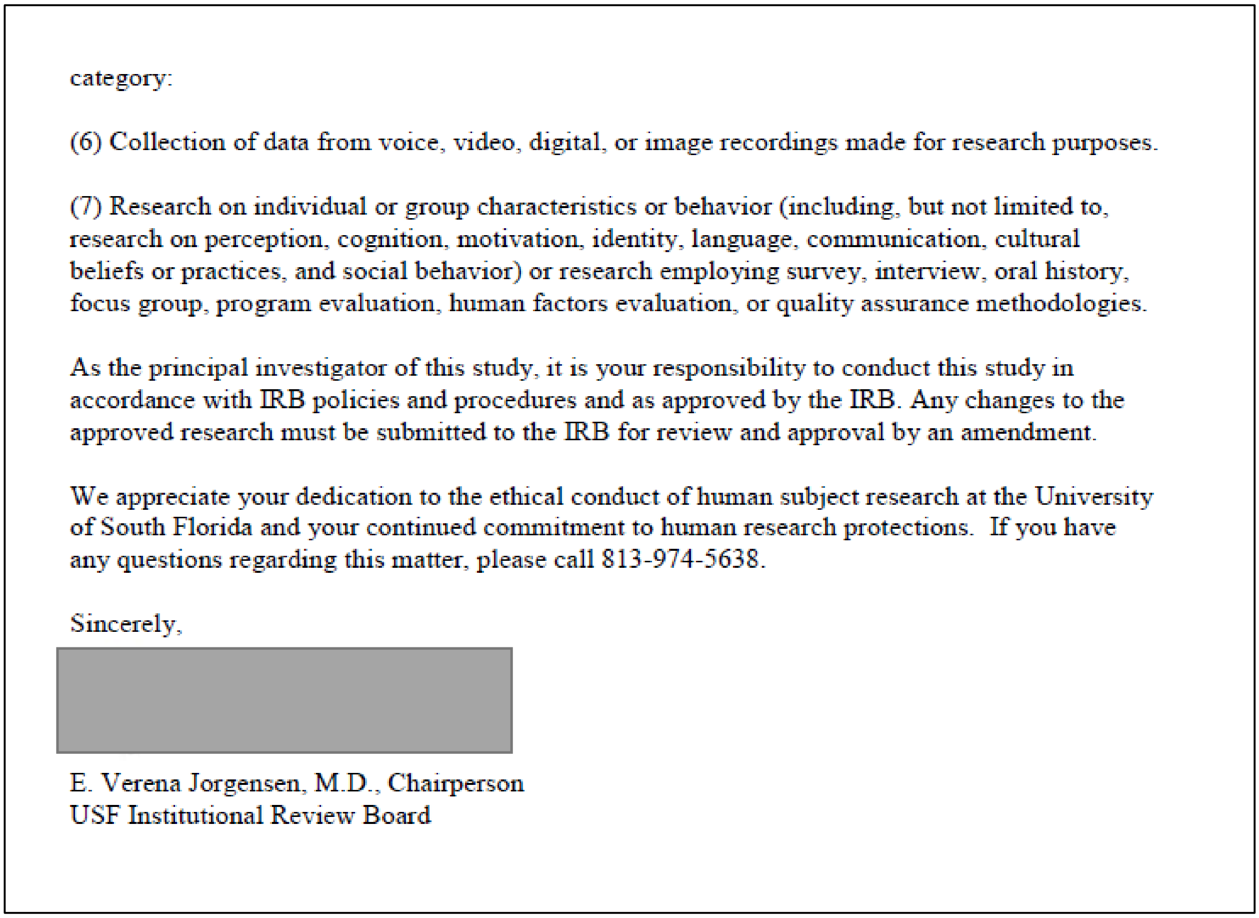
On 1/27/2015, the Institutional Review Board (IRB) reviewed and **APPROVED** the above application and all documents outlined below.

**Approved Item(s):**
**Protocol Document(s):**
Protocol.docx

**Consent/Assent Document(s)*:**
Adult IC CAREN simulator.docx.pdf

*Please use only the official IRB stamped informed consent/assent document(s) found under the "Attachments" tab. Please note, these consent/assent document(s) are only valid during the approval period indicated at the top of the form(s).

It was the determination of the IRB that your study qualified for expedited review which includes activities that (1) present no more than minimal risk to human subjects, and (2) involve only procedures listed in one or more of the categories outlined below. The IRB may review research through the expedited review procedure authorized by 45CFR46.110 and 21 CFR 56.110. The research proposed in this study is categorized under the following expedited review



category:

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB for review and approval by an amendment.

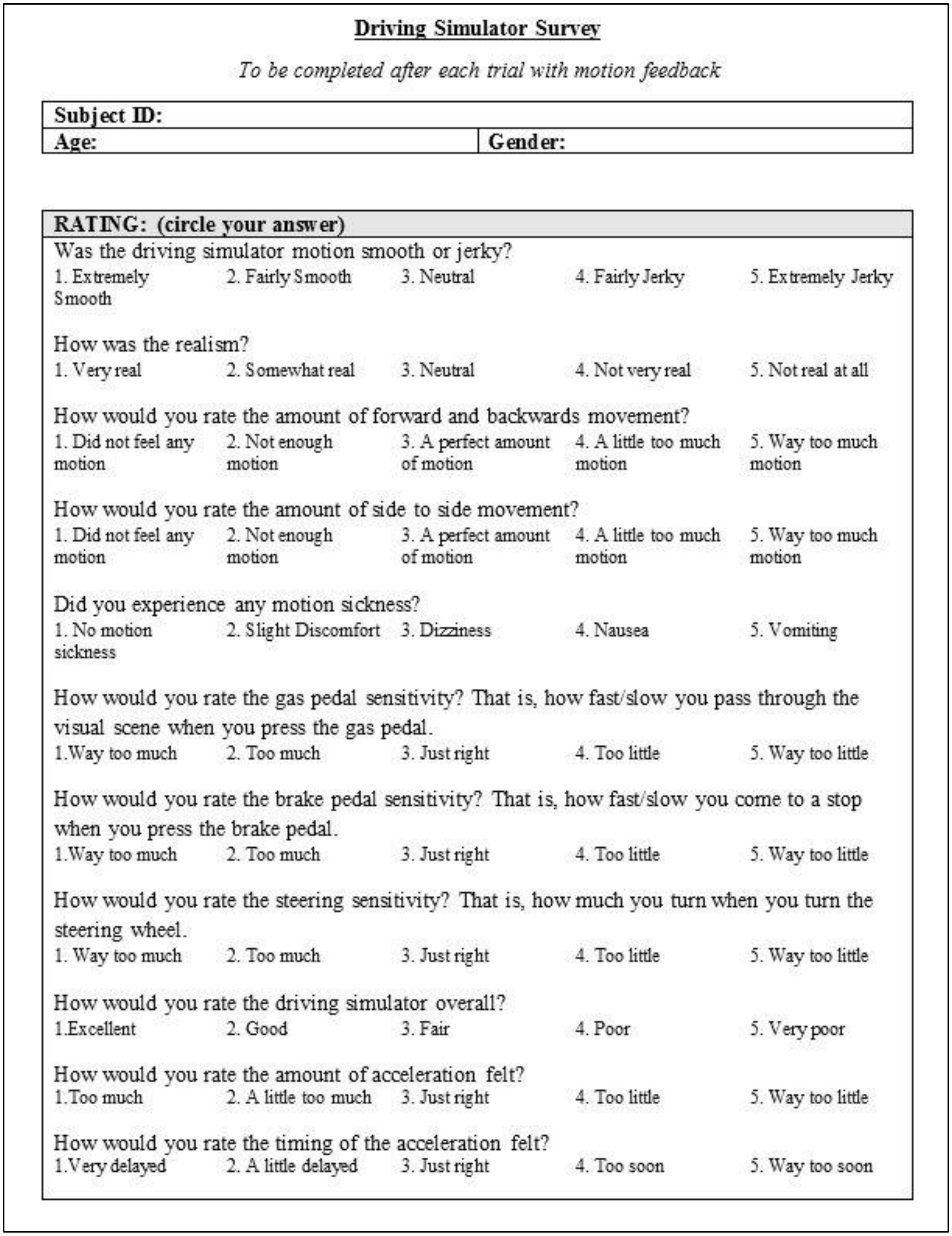
We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

[redacted]

E. Verena Jorgensen, M.D., Chairperson
USF Institutional Review Board

## Appendix E: Surveys



**Driving Simulator Survey**

*To be completed after each trial with motion feedback*

| | |
|---|---|
| **Subject ID:** | |
| **Age:** | **Gender:** |

**RATING: (circle your answer)**

Was the driving simulator motion smooth or jerky?

| | | | | |
|---|---|---|---|---|
| 1. Extremely Smooth | 2. Fairly Smooth | 3. Neutral | 4. Fairly Jerky | 5. Extremely Jerky |

How was the realism?

| | | | | |
|---|---|---|---|---|
| 1. Very real | 2. Somewhat real | 3. Neutral | 4. Not very real | 5. Not real at all |

How would you rate the amount of forward and backwards movement?

| | | | | |
|---|---|---|---|---|
| 1. Did not feel any motion | 2. Not enough motion | 3. A perfect amount of motion | 4. A little too much motion | 5. Way too much motion |

How would you rate the amount of side to side movement?

| | | | | |
|---|---|---|---|---|
| 1. Did not feel any motion | 2. Not enough motion | 3. A perfect amount of motion | 4. A little too much motion | 5. Way too much motion |

Did you experience any motion sickness?

| | | | | |
|---|---|---|---|---|
| 1. No motion sickness | 2. Slight Discomfort | 3. Dizziness | 4. Nausea | 5. Vomiting |

How would you rate the gas pedal sensitivity? That is, how fast/slow you pass through the visual scene when you press the gas pedal.

| | | | | |
|---|---|---|---|---|
| 1.Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little |

How would you rate the brake pedal sensitivity? That is, how fast/slow you come to a stop when you press the brake pedal.

| | | | | |
|---|---|---|---|---|
| 1.Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little |

How would you rate the steering sensitivity? That is, how much you turn when you turn the steering wheel.

| | | | | |
|---|---|---|---|---|
| 1. Way too much | 2. Too much | 3. Just right | 4. Too little | 5. Way too little |

How would you rate the driving simulator overall?

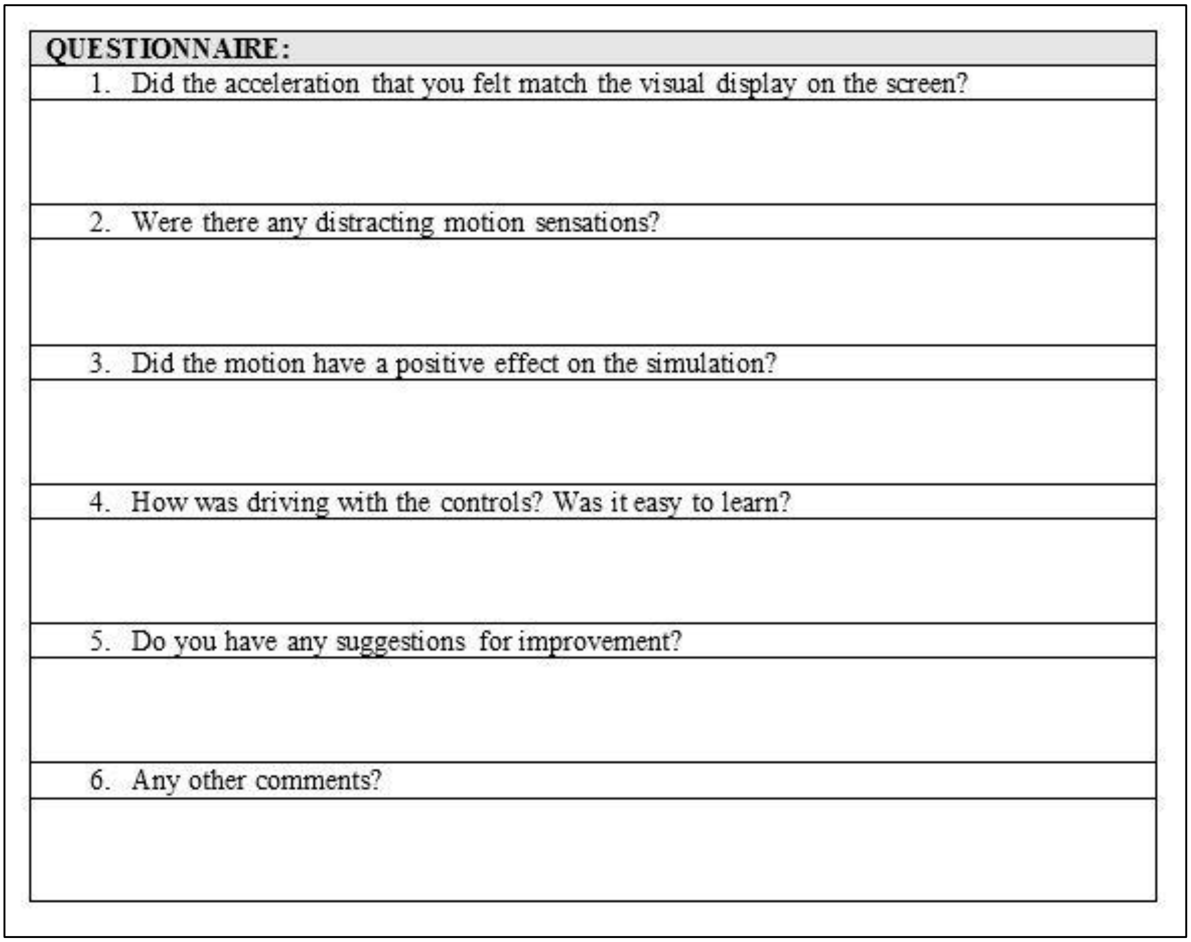
| | | | | |
|---|---|---|---|---|
| 1.Excellent | 2. Good | 3. Fair | 4. Poor | 5. Very poor |

How would you rate the amount of acceleration felt?

| | | | | |
|---|---|---|---|---|
| 1.Too much | 2. A little too much | 3. Just right | 4. Too little | 5. Way too little |

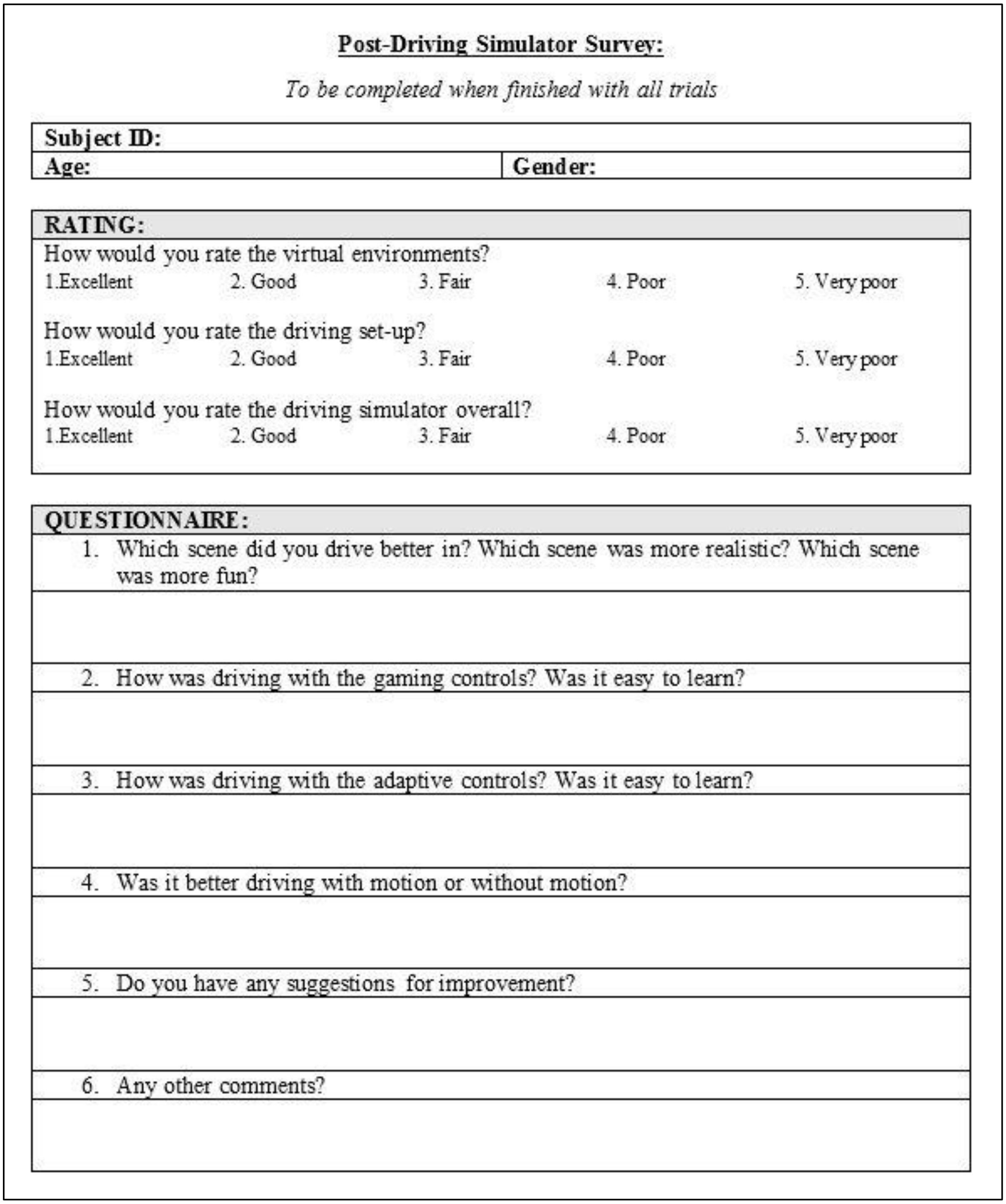
How would you rate the timing of the acceleration felt?

| | | | | |
|---|---|---|---|---|
| 1.Very delayed | 2. A little delayed | 3. Just right | 4. Too soon | 5. Way too soon |



**QUESTIONNAIRE:**

1. Did the acceleration that you felt match the visual display on the screen?
2. Were there any distracting motion sensations?
3. Did the motion have a positive effect on the simulation?
4. How was driving with the controls? Was it easy to learn?
5. Do you have any suggestions for improvement?
6. Any other comments?



## Post-Driving Simulator Survey:

*To be completed when finished with all trials*

| | |
|---|---|
| **Subject ID:** | |
| **Age:** | **Gender:** |

**RATING:**

How would you rate the virtual environments?

1.Excellent 2. Good 3. Fair 4. Poor 5. Very poor

How would you rate the driving set-up?

1.Excellent 2. Good 3. Fair 4. Poor 5. Very poor

How would you rate the driving simulator overall?

1.Excellent 2. Good 3. Fair 4. Poor 5. Very poor

**QUESTIONNAIRE:**

1. Which scene did you drive better in? Which scene was more realistic? Which scene was more fun?
2. How was driving with the gaming controls? Was it easy to learn?
3. How was driving with the adaptive controls? Was it easy to learn?
4. Was it better driving with motion or without motion?
5. Do you have any suggestions for improvement?
6. Any other comments?

## Appendix F: Results

### F.1 Rating Results

Table F.1 Rating Results for Highway Scene and Gaming Controls

| | **Subjects 1-10** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Question 1** | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 1 | 2 | - |
| **Question 2** | 1 | 4 | 2 | 1 | 3 | 2 | 1 | 2 | 2 | - |
| **Question 3** | 3 | 4 | 2 | 3 | 3 | 2 | 3 | 3 | 3 | - |
| **Question 4** | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | - |
| **Question 5** | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | - |
| **Question 6** | 3 | 3 | 4 | 3 | 3 | 3 | 4 | 3 | 2 | - |
| **Question 7** | 3 | 3 | 4 | 4 | 4 | 3 | 3 | 3 | 4 | - |
| **Question 8** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | - |
| **Question 9** | 2 | 3 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | - |
| **Question 10** | 3 | 3 | 4 | 3 | 4 | 4 | 3 | 3 | 3 | - |
| **Question 11** | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | - |

Table F.2 Rating Results for Highway Scene and Adaptive Controls

| | **Subjects 1-10** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Question 1** | 2 | 2 | 3 | 2 | 2 | 1 | 3 | 2 | 3 | - |
| **Question 2** | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 2 | 1 | - |
| **Question 3** | 3 | 3 | 2 | 3 | 3 | 2 | 2 | 3 | 3 | - |
| **Question 4** | 4 | 3 | 3 | 2 | 3 | 2 | 2 | 3 | 3 | - |
| **Question 5** | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | - |
| **Question 6** | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | - |
| **Question 7** | 4 | 3 | 4 | 3 | 3 | 3 | 4 | 3 | 3 | - |
| **Question 8** | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | - |
| **Question 9** | 2 | 3 | 2 | 1 | 3 | 2 | 2 | 1 | 2 | - |
| **Question 10** | 3 | 3 | 4 | 4 | 3 | 4 | 3 | 3 | 3 | - |
| **Question 11** | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | - |

Table F.3 Rating Results for City Scene and Gaming Controls

| | Subjects 1-10 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Question 1** | 2 | 4 | 2 | 1 | 5 | 1 | 2 | 4 | 2 | 4 |
| **Question 2** | 2 | 3 | 2 | 1 | 3 | 2 | 2 | 3 | 1 | 2 |
| **Question 3** | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 1 | 3 |
| **Question 4** | 3 | 3 | 3 | 4 | 3 | 2 | 3 | 4 | 3 | 4 |
| **Question 5** | 1 | 2 | 1 | 1 | 4 | 1 | 2 | 1 | 1 | 3 |
| **Question 6** | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 3 | 3 |
| **Question 7** | 4 | 4 | 3 | 4 | 3 | 3 | 4 | 2 | 3 | 3 |
| **Question 8** | 3 | 3 | 2 | 2 | 1 | 3 | 2 | 3 | 2 | 3 |
| **Question 9** | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 2 | 2 |
| **Question 10** | 3 | 3 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 3 |
| **Question 11** | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 |

Table F.4 Rating Results for City Scene and Adaptive Controls

| | Subjects 1-10 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Question 1** | 1 | 2 | 2 | 2 | 4 | 1 | 2 | 1 | 3 | - |
| **Question 2** | 2 | 3 | 2 | 1 | 3 | 2 | 2 | 1 | 2 | - |
| **Question 3** | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 2 | - |
| **Question 4** | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | - |
| **Question 5** | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | - |
| **Question 6** | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | - |
| **Question 7** | 2 | 3 | 4 | 3 | 4 | 3 | 3 | 3 | 3 | - |
| **Question 8** | 4 | 5 | 5 | 2 | 2 | 3 | 5 | 5 | 1 | - |
| **Question 9** | 2 | 2 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | - |
| **Question 10** | 3 | 4 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | - |
| **Question 11** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | - |

Table F.5 Rating Results for Post Survey

| | Subjects 1-10 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Question 1** | 2 | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | - |
| **Question 2** | 1 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | - |
| **Question 3** | 2 | 3 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | - |

## F.2 Questionnaire Results for Highway Environment and Gaming Controls

1. Did the acceleration that you felt match the visual display on the screen?
    a. Yes, rate of deceleration was okay but the effect of ‘slamming’ the brake wasn’t really there.
    b. Yes.
    c. The acceleration I felt seemed a little delayed and a little slow but did provide the feeling of acceleration and matched the display.
    d. Yes, but when I used the brake, I felt that the platform was a little delayed.
    e. Yes.
    f. Slightly too little acceleration.
    g. It seemed good. Once up to speed, however, the acceleration/gas pedal sensitivity did not match the visual on the screen as well but still very good.
    h. Yes, it matched perfectly.
    i. Yes. When I accelerated to turn I did not know if I was going to hit a car while passing them.
2. Were there any distracting motion sensations?
    a. At the end (of each highway simulation). The final braking motion (complete stop) feels off (plus too much ‘coasting’).
    b. No.
    c. No.
    d. No.
    e. A little dizziness.
    f. No.

   g. No.
   h. No, everything felt correct.
   i. No.

3. Did the motion have a positive effect on the simulation?
   a. Yes.
   b. Yes.
   c. Yes.
   d. Yes.
   e. Yes.
   f. Yes.
   g. Yes.
   h. Yes.
   i. Yes. Made it feel real. I was focused more on the screen (driving), I did not feel unusual motions.
4. How was driving with the controls? Was it easy to learn?
   a. At the start, the sideways steering (changing lanes) motion interfered with the straightening out, but it was adaptable (possibly by entering lane more gradually).
   b. Good, need to mount pedals down.
   c. Easy to use and learn.
   d. Yes, just as a real car.
   e. Easy.
   f. Yes, it was very easy.
   g. Yes, felt much more realistic than the hand controls.

   - h. Very simple, it is what I am used to.
   - i. Just like a regular car.

5. Do you have any suggestions for improvement?
   - a. Look into the motion while changing lanes quickly. There may be some after effect (residual) that remains after wheel is straightened.
   - b. Less shake when decelerating.
   - c. Moving the speedometer lower on the screen, maybe to the right or left of the road, it's a little high to look up at.
   - d. Adjust the brake pedal-platform movement.
   - e. Lock pedals in place.
   - f. More acceleration simulation.
   - g. This simulation felt the most realistic so far.
   - h. No.
   - i. It would be nice to see if I passed a car or not. I guess in a real vehicle you'll have side mirrors.
6. Any other comments?
   - a. Consider adding some haptic feedback to braking (like ABS creates) and harsher braking (I noticed I would tilt back the whole pedal assembly at final braking).
   - b. n/a.
   - c. The cars on the road seemed to drive less than the 70 mph speed limit.
   - d. It was really good.
   - e. n/a.
   - f. n/a.

   - g. No.
   - h. n/a.
   - i. n/a.

### F.3 Questionnaire Results for Highway Environment and Adaptive Controls

1. Did the acceleration that you felt match the visual display on the screen?
   - a. Yes.
   - b. Yes.
   - c. A little delayed but pretty close.
   - d. Yes.
   - e. Yes.
   - f. Slightly not enough.
   - g. They were well matched I thought.
   - h. Yes, it matched almost spot on.
   - i. Yes, it did.
2. Were there any distracting motion sensations?
   - a. Just in the side to side motion and possibly the final braking.
   - b. No.
   - c. No.
   - d. No.
   - e. No.
   - f. No.
   - g. When changing lanes it did not feel very realistic. It seemed like you were turning on a point not changing lanes.

   h. The “car” felt as if it was pulling to the sides.
   i. When I was turning right, I didn’t know if I was going to collide with the car I just passed.

3. Did the motion have a positive effect on the simulation?
   a. Yes, especially in forward/back (acceleration/deceleration) but I feel it may have caused some over correction in side to side steering.
   b. Yes.
   c. Yes.
   d. Yes, but I would increase the side to side motion.
   e. Yes.
   f. Yes.
   g. Yes.
   h. I felt as if it pulled too much to simulate an actual vehicle.
   i. Yes. Made it real.
4. How was driving with the controls? Was it easy to learn?
   a. Yes, it was fairly easy. Turning back to center was still intuitive.
   b. Yes, controls were fair.
   c. Difficult, but easier than the city scene since there were no turns. Relatively easy to learn.
   d. It was okay (like playing a video game), but I’m not used to that steering wheel.
   e. After practice it wasn’t too hard.
   f. The forward/brake control was easy. The steering was difficult to stay centered and required constant adjustment.

   g. Yes, the sensitivity was good. It would be better if the straight position was at the top not to the side but was learned quickly.
   h. Yes, very simple to learn and the controls worked well.
   i. Turning wheel was confusing. Turned too quick.
5. Do you have any suggestions for improvement?
   a. Adjust the side steering motion maybe (it may have just been timing that caused overcorrecting).
   b. Make the cars on the highway simulation move faster. At least 55 mph.
   c. Move the speedometer down on the screen. Speed up the other cars in the simulation.
   d. More platform motion when the brake is used.
   e. Longer practice. If possible, show cars behind or to the side, don’t allow car to merge over as soon when other cars are right beside it.
   f. Less sensitive steering or automatically lock in center when not turning.
   g. The brake with the visual seemed a little off and the motion for changing lanes seemed to vary in sensitivity, it was a little jerky.
   h. Can tighten the steering.
   i. I liked driving straight more than turns.
6. Any other comments?
   a. n/a.
   b. Pedals mounted on floor.
   c. Seemed realistic, easier to use the controls.
   d. It was really nice.

    e. n/a.
    f. n/a.
    g. No.
    h. n/a.
    i. I was paying more attention to cars, not colliding, than the speed.

### F.4 Questionnaire Results for City Environment and Gaming Controls

1. Did the acceleration that you felt match the visual display on the screen?
    a. Yes.
    b. Yes.
    c. Yes.
    d. Yes.
    e. Slightly off.
    f. Slightly too little.
    g. Yes, the motion and visual matched the acceleration I thought I was giving.
    h. Yes, it did.
    i. Yes. Seem that the steps I was taken was smoothly transmitted to the actions.
    j. Yes.
2. Were there any distracting motion sensations?
    a. No.
    b. Yes, when stopped at a red light the platform moved forward.
    c. No.
    d. No.
    e. Dizziness/motion sickness.

   f. No.

   g. There was a little uneasiness in feeling but I think it was just getting used to the room and simulation.

   h. Yes, after turning at a light the platform would jerk.

   i. No. One time when I turned too fast, I felt the side movement.

   j. No.

3. Did the motion have a positive effect on the simulation?

   a. Yes.

   b. Yes.

   c. Yes.

   d. Yes, but the brakes were delayed.

   e. A little too much motion.

   f. Yes.

   g. Yes, I think it was realistic enough to be effective.

   h. The motion made me correct steering.

   i. Positive. Seem real.

   j. Yes, it added a more realistic feel.

4. How was driving with the controls? Was it easy to learn?

   a. Difficulty due more to haptic feedback in the wheel possibly. (It seemed as though it was trying to simulate the centripetal acceleration but the ratio between stiffness and looseness impeded steering.

   b. Okay, the pedals moved forward and steering mount moved while driving.

   c. Easy to learn, seemed very sensitive.

    d. Yes, it was nice.
    e. Yes-steering was a little too sensitive.
    f. The gaming steering and foot controls are very easy to use.
    g. Yes, it was realistic enough to match real driving.
    h. Very easy.
    i. Easy to learn. Just like a real car.
    j. It felt very similar to real life, and it was easy to learn.

5. Do you have any suggestions for improvement?
    a. Accelerations matched the steering but I had some difficulty with steering here as well (primarily the large curves while up to speed).
    b. Mount pedals to a flat piece of wood.
    c. Steering and gas seemed a little bit too much sensitivity, so making them less sensitive may help.
    d. Adjust the brakes.
    e. Display speed in red when over limit. Less steering sensitivity.
    f. Yellow light appears to always be on.
    g. The turning sometimes did not return to straight like in a real car. A lot of steering input was needed and the car seemed to wander on the road.
    h. I think the controls did not respond well to slowly returning the steering wheel to neutral position.
    i. The steering wheel is still sensitive.
    j. Maybe a fan would help with motion sickness.

6. Any other comments?

a. n/a.
b. n/a.
c. I moved the pedals accidently during the simulation, so missed the brake on one of the stops. One time after the light turned green and I took a left it said I ran a red light.
d. n/a.
e. n/a.
f. n/a.
g. No, the above is all I could see to improve upon.
h. n/a.
i. Seems in straight path easier to control. In curves, it was shaky.
j. n/a.

### F.5 Questionnaire Results for City Environment and Adaptive Controls

1. Did the acceleration that you felt match the visual display on the screen?
    a. Yes.
    b. Yes.
    c. Yes.
    d. Yes.
    e. Yes.
    f. Slightly too little acceleration was felt.
    g. Yes.
    h. Yes, it matched it perfectly.
    i. Yes.

2. Were there any distracting motion sensations?
    a. No.
    b. No.
    c. No.
    d. No, I felt it was real.
    e. No.
    f. No.
    g. Not really.
    h. None at all everything felt normal.
    i. No.
3. Did the motion have a positive effect on the simulation?
    a. Yes (took corners slowly though, appears to match (everything felt ordinary for speed) but not sure if I went faster).
    b. Yes.
    c. Yes.
    d. Yes.
    e. Yes.
    f. Slightly positive effect.
    g. Yes, I think so.
    h. Felt very real.
    i. Yes. Made it feel real.
4. How was driving with the controls? Was it easy to learn?

   a. Good, just large amount of turns for straightening out (may be fine so long as the ratio between turns needed for corners matches).
   b. Fair.
   c. Driving with the controls was very difficult, particularly the steering. After several minutes, I felt like I sort of figured it out. More difficult to learn than the game controls.
   d. Easy to learn, but I prefer the regular controller.
   e. Harder.
   f. The forward/brake control was easy. The steering was slightly difficult.
   g. Yes, they were okay once getting used to.
   h. The steering control is the only one I had issues with.
   i. Were difficult when using for first time. Turning was very sensitive.

5. Do you have any suggestions for improvement?
   a. Possibly adjust steering wheel turn count ratio for corner turn vs straightening out.
   b. Stop on red and turn light is legal.
   c. The steering seemed like I had to make too many revolutions to make a small change in direction and to turn.
   d. Use the other controller with platform movement.
   e. Allow for practice. Less sensitivity on steering. Blinker.
   f. Make forward orientation more accessible on steering control.
   g. Overall great but the turning did not seem realistic especially on right turns it seemed. Way too much wheel input for the visual on the screen.
   h. If the steering control can tighten as you reach its limit.

    i. The turning control, the user needs some practice.

6. Any other comments?
    a. n/a.
    b. Steering wasn't sensitive enough.
    c. The dynamic feedback was very helpful and improved the simulation. Moving the speedometer lower on the screen would also help.
    d. Even without platform movement, the simulation was excellent. I visually felt that I was using the brakes.
    e. n/a.
    f. n/a.
    g. No.
    h. n/a.
    i. With training, I think it becomes easier to use.

### F.6 Questionnaire Results for Post-Survey

1. Which scene did you drive better in? Which scene was more realistic? Which scene was more fun?
    a. Highway. City. City. But preferred having the cars on the highway.
    b. Highway. City. City.
    c. Drove better on the highway. Highway was more realistic. City scene was more fun.
    d. The highway was better, more realistic and more fun.
    e. The highway scene was easier and more realistic but city scene was more fun.

   f. I drove better on the highway since less turning and braking was required. However, the highway scene was more fun as moving through traffic is more exciting than stop lights.
   g. I think I drove on the highway better especially with regular controls it felt just like the real thing. I think the highway was also more realistic but the city was more fun with the turning and stopping.
   h. I drove better on the highway scene. I would evenly rate the highway and city. The city scene.
   i. Expressway, straight line with actual steering wheel. Inside the city. City.
2. How was driving with the gaming controls? Was it easy to learn?
   a. I could adapt to them after a little but some instances of sideways motion made control a little more difficult.
   b. Easy to learn.
   c. Gaming controls was easy to learn and seemed pretty realistic.
   d. Easy, just like a video game.
   e. Yes, easy to learn.
   f. They were very easy to learn and use.
   g. Very easy to learn.
   h. Very easy to learn. I am used to those controls.
   i. Yes, more practice made it better to work with/use.
3. How was driving with the adaptive controls? Was it easy to learn?
   a. (Same as above) and too many turns needed in city scene.
   b. Took some time, but I learned.

c. The adaptive controls were hard to learn and more difficult to use in the city scene. Hard to tell where the steering wheel was, centered, turned all the way, etc.
d. It was way too sensitive, but it was easy to learn.
e. After practice it was easier.
f. The forward/brake control was very easy. The steering took some practice and was difficult to keep straight.
g. It took a little more getting used to but could learn quickly in practice. One time in the city I got confused for a second with which hand did steering and which did brake/acceleration.
h. The steering on the adaptive controls was difficult to operate.
i. Took more practice, but user friendly.

4. Was it better driving with motion or without motion?
   a. Control was better without during highway scene. However, it was more preferable for the motion. Much better "test" and more realistic.
   b. Without motion.
   c. Better driving with motion.
   d. It was better with motion.
   e. With motion made it feel more realistic.
   f. With motion added helpful feedback.
   g. With motion felt more realistic. Without motion I could sense myself still leaning forward when coming to a stop.
   h. The motion felt right.

    i. Did not make a difference. I was not paying attention to motion but speed limit and not colliding.

5. Do you have any suggestions for improvement?
    a. Mainly just some adjustment to residual movement after steering into a new lane, etc. (possibly just with timing).
    b. Mount pedals to ground.
    c. Move the speedometer lower on screen, especially in highway scene, maybe in grass. Secure the foot pedals so they don’t move. Adjust the adaptive control sensitivity, especially for the city scene. Speed up the other cars on highway or lower the speed limit.
    d. Fix the brake feedback, it is a little delayed.
    e. Give subjects time to practice in city scene with both controls.
    f. Slightly more acceleration should be experienced. Adaptive steering could be adjusted to better stay straight.
    g. Overall really great and realistic. The hand controls on the highway felt unrealistic when changing lanes and was jerky when driving straight. The hand controls in the city also had very unrealistic inputs for steering. I had to go all the way to lock to make the turn then five full turns the opposite way to straighten out. In the city none seemed to really have the gyroscopic effect of the car moving straight with the application of the gas. On the outside loop of the city the game controls you had enough play in the wheel you could come out of the corner and keep the wheel to the left and the car seemed to go straight for a while longer.

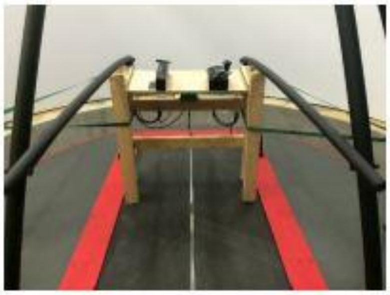
    h. Just the steering if can have feedback. In the sense that it will tighten as the limit is reached.
    i. Adaptive control wheel had to remember which way turns where. Shaky when turning.

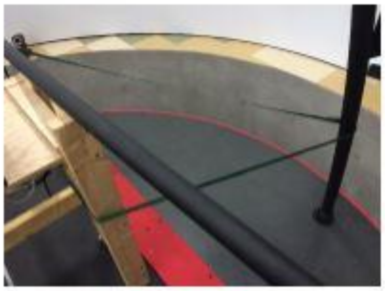
6. Any other comments?
    a. I’m used to driving barefoot (so that could be why I had some difficulty in gas sensitivity (I based lowering my foot more on visuals than feeling pedal)). Did not monitor speed as much. Display up a little too high out of visual range. Possible add coasting. Right turn on red after stop.
    b. Speed up cars on highway.
    c. It was very realistic, especially with the dynamic motion.
    d. Nice job!
    e. n/a.
    f. n/a.
    g. n/a.
    h. n/a.
    i. I like the set up. Simple and effective.

## Appendix G: Operating Procedures

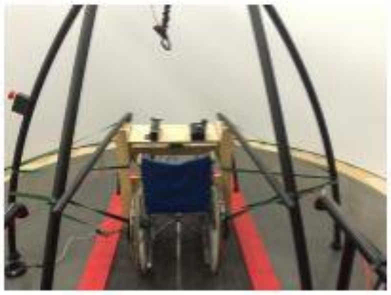
### Driving Simulator Procedures

1. Turn the CAREN system on using the standard procedures
2. Move the platform to the settled position and move the walkway to meet the platform
3. Plug the USB cord into the D-Flow computer
4. Plug the extension cord into the wall underneath the white board
5. One person hand the USB and extension cords to another person who is standing on the platform
6. Carry the gaming controls on to the platform
7. Two people carry the table onto the platform and set in place
8. Ratchet the table to the platform using two ratchet straps





9. Put the safety harness on the subject
10. Instruct the subject to walk on the platform
11. Attach the safety clip to the safety harness
12. Push the wheel chair on the platform and have the subject sit down
13. Adjust the wheelchair position and lock the wheels in place
14. Ratchet the wheelchair to the platform



15. If using adaptive controls, make sure the controls are bolted to the table and plug in the USB cord from the green box
16. If using gaming controls, make sure the steering wheel is secured to the table and plug in the power and USB
17. Move the platform to neutral position
18. Engage the platform and start the application