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Assessing the Impact of Multi-variate Steering-rate Vehicle Control on Driver Performance in a Simulation Framework

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ASSESSING THE IMPACT OF MULTIVARIATE STEERING-RATE VEHICLE CONTROL ON DRIVER PERFORMANCE IN A SIMULATION FRAMEWORK

by

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ABSTRACT

When a driver turns a steering-wheel, he or she normally expects the vehicle's steering system to communicate an equivalent amount of signal to the road-wheels. This relationship is linear and occurs regardless of the steering-wheel's position within its rotational travel. The linear steering paradigm in passenger vehicles has gone largely unchanged since mass production of passenger vehicles began in 1901. However, as more electronically-controlled steering systems appear in conjunction with development of autonomous steering functions in vehicles, an opportunity to advance the existing steering paradigms arises. The following framework takes a human-factors approach toward examining and evaluating alternative steering systems by using Modeling and Simulation methods to track and score human performance.

Present conventional steering systems apply a linear relationship between the steering-wheel and the road wheels of a vehicle. The rotational travel of the steering-wheel is 900° and requires two-and-a-half revolutions to travel from end-stop to opposite end-stop. The experimental steering system modeled and employed in this study applies a dynamic curve response to the steering input within a shorter, 225° rotational travel. Accommodation variances, based on vehicle speed and steering-wheel rotational position and acceleration, moderate the apparent steering input to augment a more-practical, effective steering rate. This novel model follows a paradigm supporting the full range of steering-wheel actuation without necessitating hand repositioning or the removal of the driver's hands from the steering-wheel during steering maneuvers.

In order to study human performance disparities between novel and conventional steering models, a custom simulator was constructed and programmed to render representative models in a test scenario. Twenty-seven males and twenty-seven females, ranging from the ages of eighteen to sixty-five were tested and scored using the driving simulator that presented two successive driving test vignettes: One vignette using conventional 900° steering with linear response and the other employing the augmented 225° multivariate, non-linear steering.

The results from simulator testing suggest that both males and females perform better with the novel system, supporting the hypothesis that drivers of either gender perform better with a system augmented with 225° multivariate, non-linear steering than with a conventional steering system. Further analysis of the simulated-driving scores indicates performance parity between male and female participants, supporting the hypothesis positing no significant difference in driver performance between male and female drivers using the augmented steering system. Finally, composite data from written questionnaires support the hypothesis that drivers will prefer driving the augmented system over conventional steering.

These collective findings support justification for testing and refining novel steering systems using Modeling and Simulation methods. As a product of this particular study, a tested and open-sourced simulation framework now exists such that researchers and automotive designers can develop, as well as evaluate their own steering-oriented products within a valid human-factors construct. The open-source nature of this framework implies a commonality by which otherwise-disparate research and development work can be associated.

Extending this framework beyond basic investigation to reach applications requiring more-specialized parameters may even impact drivers having special needs. For example, steering-system functional characteristics could be comparatively optimized to accommodate individuals afflicted with upper-body deficits or limited use of either or both arms. Moreover, the combined human-factors and open-source approaches distinguish the products of this research as a common and extensible platform by which purposeful automotive-industry improvements can be realized—contrasted with arbitrary improvements that might be brought about predominantly to showcase technological advancements.

I proudly and lovingly dedicate this research and dissertation work to my father, Athanasios (Tom) Stathis Xynidis. His exemplary roles in family, church, country and his contributions to this world have always been my inspiration.

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CHAPTER 1: INTRODUCTION

Background

Consider the function of steering. Alongside engine throttle, steering is certainly among the most-used and most important (driver) control inputs in road vehicles today—as it has been since the introduction of the automobile steering-wheel in 1894. When one considers the importance and complete ubiquity of steering systems in passenger road vehicles, the gap becomes apparent between the degree to which the fundamental paradigm and design of steering systems have advanced when compared with the development of other automotive systems such as propulsion, suspension, and environmental/climate. Some of the more notable advancements in steering systems have been rack-and-pinion steering by BMW in 1933 with its 303 model (Sherman, 2012) (although first introduced to the US market in the 1951 MG TD) (Green, 1997) and variable rate (variable-rack/fixed-pinion) steering by Arthur Ernest Bishop in the 1970s (Bishop, 1973). Hydraulic power-assisted steering was patented by Francis W. Davis of Pierce Arrow in 1926 (Davis, 1932), however was later reintroduced commercially by General Motors in its Chrysler Imperial model and branded "Hydraguide" in 1951 (Lamm, 1999), and electric power-assisted steering as first seen with the Suzuki Cervo in 1988. In 1985, Honda became the first of many Japanese cars to offer four-wheel steering (Sherman, 2012).

The two areas of recent development that are relevant to this proposed research effort are (1) Variable-rate steering, and (2) Steer-by-wire systems. The former, as designed by Bishop (1973), implements a progressively higher rate of steering toward the steering-wheel ends, relative to the rate at steering-wheel center. This is intended to provide quicker vehicle response, but the overall function is not adaptable to vehicle speed. More-recent variable ratio steering systems are typically variations of BMW's Active Steering (Kumar & Kamble, 2012), which aims to reduce the number of steering-wheel turns from the conventional two-and-a-half turn, to less than two turns in low-speed/parking-lot situations (Koehn & Eckrich, 2004). These systems implement a combination of planetary gears and an electric motor to synthesize the effective steering input.

Steer-by-wire has been pioneered in passenger cars by Nissan with its Infinity Q50 (Ulrich, 2014). Another vehicle employing steer-by-wire technology is the Mercedes-Benz multipurpose auto-four-wheel-drive truck called the Unimog—although it is currently a concept vehicle, it received German “Straßenzulassung” (road legal) approval for a Steer-by-Wire system (Schmitt, 2011). Andonian et al. (2003) add a feedback actuator to provide haptic response in their steer-by-wire patent.

The task associated with this proposed research framework is to bridge these two areas (steer-by-wire and variable-rate steering), while introducing formulae for optimizing steering ratios (with respect to both speed and task) as well as providing a means of eliminating the need for hand-over-hand steering-wheel manipulation, which is normally necessary to maintain or regain vehicle control. The mitigation of unnecessary steering-wheel manipulation will be accomplished by constraining end-to-end steering-wheel rotation to 225°—an angle which is nominally achievable by a human driver without reconfiguring his or her hand placement, and (conveniently) exactly one-quarter the angular distance of conventional two-and-a-half turn (900°) steering systems. Such a steering system would require multivariate variability (i.e. vehicular velocity; steering-wheel angular displacement; rate and acceleration of the steering-wheel angular displacement) in order to dynamically vary an otherwise linear steering ratio. Without such accommodation, all steering input would simply result in a linear four-fold increase in steering ratio without regard to vehicle speed or steering task.

Even though a large steering-rate increase would result in greatly reduced steering-wheel rotation at low speeds, which could be advantageous and considered desirable in parking lot situations (e.g. parallel parking and three-point turns), increasing a vehicle steering rate by a four-fold linear rate at highway speeds would not be so desirable. It would make vehicle control much too difficult due to the ratio having an inverse effect on the stability and precision of a driver’s steering-wheel movements given the effect that the increased speed would have on vehicle control. Controllability at higher speeds and manageability at lower speeds are factors that seem to present opposing requirements.

Conventional steering systems deliver a compromise that is widely accepted, but these systems present a paradigm that has gone largely unchanged for several decades. In order to update the paradigm to one that is optimal for both factors, the assay of its evolution must be updated as well.

The approach followed in this study seeks to adapt steering-rate management to both vehicle velocity and the driver's task as a system, as well as to measure the effectiveness of the system (in terms of both improved vehicle control and driver acceptance) by means of a driving simulator based experiment. In order to better understand and measure the effect of such steering-system dynamics during and following experimentation, a novel simulator that can be customized to render test scenarios and support the associated metrics is necessary.

Current Problems

The fundamental principles of automobile steering systems have remained virtually unchanged for the past 90 years. As could be expected (assuming there are existing and unaddressed shortcomings and problems with conventional steering), there is likely to be plenty of room for improvement. Moreover, any claim to have produced an improved method of steering must be evaluated, based on standardized criteria and measured through simulation and ultimately in a live environment.

Problems with Conventional Steering

Every driver explicitly and/or intuitively realizes that an n-degree angular displacement of a steering-wheel for a given time moment has a greater and greater effect as vehicle speed increases (e.g. a 15° deflection of a steering-wheel for one second at 70 m.p.h. has a markedly greater effect on a vehicle's path than the same maneuver at 10 m.p.h.) There exists a non-proportionality of steering input effect across the range of a vehicle's velocity. A driver must be cognizant of the discordance between steering input and vehicle response at varying speeds if he or she is to predict the results of his or her steering inputs at various speeds. A relevant example would be over-correction, defined as excessive steering input in response to a panic reaction causing the driver to lose control of the vehicle, which is more likely to occur as vehicle velocity increases (Spainhour & Mishra, 2008).

Many maneuvers, such as parallel parking, 3-point turns, and even extreme left or right turns in city driving require releasing one's hands from their 9-and-3 o'clock (or 10-and-2 o'clock) positions and either shuffling the steering-wheel or repeating a hand-over-hand repositioning on the wheel in order to complete the maneuver while alternating moments of two-handed control versus one-handed control. Some of these maneuvers (e.g. parallel parking) require reorientation of a driver's upper body towards the rear of the vehicle in order to attend to and negotiate nearby obstacles and parking-space limits.

At higher speeds, if a driver encounters an emergent situation requiring quick hand-over-hand steering, he should anticipate that recovery from the maneuver (steering-wheel reversal) will necessitate similar efforts in order to recover and stabilize the vehicle. The cognitive demand for the driver who has not yet developed adequate skills to negotiate the primary and secondary task demands needed to perform vehicle recovery may exceed that of a novice driver (Patten et al., 2006); tracking the orientation of the steering-wheel (relative to center) is compounded with this sort of hand repositioning. Moreover, from the perspective of accommodating automated driver assistance, there are no standardized provisions in conventional steering systems to interface with safety mechanisms such as vehicle roll-over prevention or other interventions.

Problems with Mechanical Variable-rate Steering Systems

Mechanical variable-rate steering systems do not eliminate hand-over-hand repositioning (or shuffling), cannot be reconfigured, and (because of mechanical linkage) cannot be easily moved to accommodate a left-seat or right-seat driver or retracted in the case of semi-autonomous vehicles. Additionally, mechanical systems are not modular; the components comprising the rate-translation mechanism (usually a system of electric motors and planetary gears) cannot simply be swapped into another make of automobile, or for that matter, type of vehicle—such as watercraft or aircraft.

Sparse Information Regarding Alternative Paradigms

In and of itself, the development of a new steering system—as a component of a steer-by-wire system—should not be bound to the paradigm of conventional steering. Not without good reason, and not without a study of alternative paradigms with respect to conventional two-and-a-half turn (900°) steering systems. The objective of this study is to evaluate (through simulation) the effectiveness of a novel, programmable, computer-controllable steering system that allows a full range of steering without interrupting two-handed steering-wheel control, and similarly evaluating a conventional system for purposes of comparison. Literature addressing such technologies neither concludes nor disputes the effectiveness or adoptability of such a system. The referenced literature is reviewed in detail in the second chapter: "Literature Review of Relevant Technology".

In order to study the effectiveness of alternative steering control schemes, the research framework would require a specialized/customizable driving simulator to both employ installable code libraries implementing necessary input/output steering algorithms, and also measure the performance of participant drivers in specific testing scenarios. Additionally, participants will be surveyed (Likert style) in order to produce a qualitative assay of preferences and adoptability. This methodology is described in detail in the third chapter: "Experimental Methodology".

Suitable simulator hardware will consist of a programmable/configurable modular platform with standardized input/output communications with the steering-wheel (for steering-input/haptic-output) and standardized input/output connectivity to a laptop computer equipped with the specialized simulator software (which corresponds to a vehicle control unit for steering-output/vehicle-speed control and inertial-measurement data). This methodology is also described in detail in the third chapter: “Experimental Methodology”.

Motivation

The need for this study is motivated by observation that advancements in automotive steering technologies focusing on steering-wheel control are relatively sparse. More specifically, few technologies challenge the paradigm of conventional steering, which requires alternating control of the steering-wheel between hands while undertaking certain steering maneuvers (i.e. hand-over-hand, or shuffle steering methods used during turns and parking). Moreover, recent technologies that do address reduction of wheel turns, do not employ methods to completely mitigate interruption of two-handed control during those types of maneuvers, only to reduce it (Kumar & Kamble, 2012).

Accordingly, no study providing results associated with implementing an alternative system that would allow constant two-handed control while adequately accommodating the relevant human biomechanics involved in steering has been published. Consequently (short of building a real-world test vehicle), measuring the significance any results realized from comparing conventional with alternative steering technologies would necessitate a novel simulation framework that would do the following:

- Support programmable steering algorithm input.
- Provide a physics engine to apply the steering input to a model.
- Provide a means of scoring the performance of a driver.

The intent driving this research is that it will not only contribute to the academic body of knowledge, but that industry might develop more-intuitive, better-performing, and safer steering systems that can be matched with other advanced vehicle control technologies such as active-braking, active-steering, and roll-over prevention.

Research Taxonomy

The areas of interest concerning the current knowledge and technology related to the topic of this study form a clear taxonomy. The questions designed to explore this information (within the scope of this study) can be grouped accordingly.

Current Technology in Vehicle Control

1. Does the ability to maintain two hands on a steering-wheel equate to better control?
2. Does a variable-rate steering ratio equate to better control?
3. What steering-wheel ratios (relative to linear) are best suited to different speeds?

Driver

1. Kinematics: What is the ideal range of motion enabling both hands stay in place (i.e. the range of steering-wheel rotation that allows fixed hand placement through a maneuver)?
2. Will results in either acceptance or training be demographically distinguishable (e.g. novice drivers versus experienced or expert Gamepad generation versus Slide-rule generation; male versus female)?
3. Will consumers accept/adopt or even prefer a new steering paradigm?

Simulator

1. How does industry test effectiveness of steering systems in the real world?
2. What kind of simulation environment would be sufficient to virtualize an industry-type test?
3. What is the dynamic equation that describes the effect upon the input signal from the steering-wheel that translates to the desired road-wheel control signal?
4. How should driver performance be measured?
5. How would operator acceptance be measured?
6. Can a simulator be built to employ these metrics and be affordable at an academic level?

The literature relevant to the investigation of these questions is reviewed in detail in the second chapter: "Literature Review of Relevant Technology", including a section discussing the gap in the current research and the resulting research questions driving the study.

Assumptions, Limitations, and Scope

The test track that will be simulated in the experiment will consist of a slalom course using traffic cones (stanchions) interspersed at distances commonly used in industry standard vehicle testing. It is beyond the scope of this research to derive and design optimal testing parameters, with respect to track dimensions; rather, acceptable de facto slalom course parameters will be adopted, based on consultations with driving and vehicle-performance experts. It is also beyond the monetary resources of this study to manufacture a real-world steering input control device that could be installed in a vehicle for testing on a closed-circuit track.

The nature of the experiment requires a specialized simulation framework having specific customizable features, or access to program internals that would allow track customization, object/vehicle collection detection, 3D VR integration, and programmability to the degree of supporting custom steering ratio algorithms. Limited by monetary constraints, an open-source driving-simulator platform, which is widely used in academic research, was selected and modified accordingly. The software platform was integrated with Commercial off-the-Shelf (COTS) hardware. The same limitation excludes the possibility of validating the specialized system in a real-world car and track. Both the software platform (TORCS/Speed Dreams and Unreal rendering engine) as well as the hardware (Logitech Wheel and Seating System; Oculus Rift) will be discussed in the Literature Review and Methodology sections.

The proposed research platform is intended to have utility beyond the scope of this experiment. For example, while not being specifically addressed in this research, the 3D VR device will accommodate more-complex scenarios requiring much broader fields of vision, such as parallel parking, decreasing-radius freeway exits, or even the “rubbernecking” phenomenon. However, practical limitations constrain this study to evaluating human performance using a slalom course on a straight track.

Summary of Subsequent Chapters

The following chapter reviews the academic and industry literature that establishes the groundwork for the final research methodology. It begins with an overview of the chapter. Subsequent sections address *Milestones* and *State-of-the-Art* in steering systems, *Safety* in indirect controllers, *Human Factors considerations*, *Standards and Practices in Automotive Testing*, an investigation of *Simulation Software and Associated Hardware*, and conclude by *Identifying the Gap in Current Research* and the resulting *Research Questions* that justify the research.

CHAPTER 2: LITERATURE REVIEW

Overview

When one considers the major advancements made throughout automotive history, the more-dominant subjects of economy, performance, comfort and style typically come to mind. Advancements in the area of steering systems accordingly take a back seat by comparison. This review will examine the major historical advancements in steering operations, and then take a look at current state-of-the-art of manual steering technology as well as the availability of software and hardware platforms that can be used to develop steering system theories and the framework upon which to develop them. Subsequent sections of this literature review aim to identify the problems or shortcomings of conventional steering systems, as well as more-advanced steering systems in terms of both safety and contribution to steering competence. Having established these foundations, broader perspectives such as human factors and the biomechanics associated with steering will be explored in an effort to present design requirements for designing steering systems to accommodate human systems, rather than the other way around.

Testing is an important part of developing a concept before realizing a real-world end product. Accordingly, this review will investigate methods of testing employed by the automotive industry to evaluate their own research and development. Furthermore, since the physical construction of a steering system and incorporating it into a vehicle is beyond the practical scope of this research, a system will be virtualized as a simulation, borrowing from relevant testing methods used in the automotive industry. And finally, the components of the simulation will be addressed, as will be the topic of validating the product simulator.

Historical Milestones in Steering Systems

Alongside engine throttle, steering is certainly among the most-used (human) control inputs in road vehicles today—as it has been since the introduction of the automobile steering wheel in 1894; the first notable improvement being its placement on a raked column in 1898 by Panhard (Lay & Vance Jr, 1992). From there, other “innovations” were introduced. In 1965, the Ford Motor Company tested a concept they called, “Wrist Twist”. It consisted of two 5” rings (wheels) mounted on a two-pronged beam roughly shoulder width apart, and comfortably within driving reach (with arms on armrests). The rings were coupled, and moved simultaneously, allowing the driver to alternate ring rotation between each hand as an analog to hand-over-hand steering wheel manipulation. Although the system was not brought to mass production in standard automobiles, the concept has been applied to the more specialized area of special vehicle controls for severely disabled drivers (Bray & Cunningham, 1967).

Hydraulic power-assisted steering was invented by Francis W. Davis of Pierce Arrow in 1926 Davis (1932). Much later, General Motors commercially reintroduced hydraulic power-assist in its Chrysler Imperial as “Hydraguide” in 1951, whereas electric power-assist only appeared in 1988 in the Suzuki Cervo (Lamm, 1999). BMW introduced rack-and-pinion steering in 1933 with its 303 model (Sherman, 2012), however rack-and-pinion steering was first introduced to the US market in the 1951 MG TD (Green, 1997). In 1985, Honda became the first of many Japanese cars to offer four-wheel steering (Sherman, 2012).

Autonomous steering functions such as lane keeping and self-parking are unquestionably advancements in steering technology; however, vehicular steering autonomy does not play a role which would be considered within the scope of this research—which is manual, human-in-the-loop control—and therefore not reviewed within the context of this research. Steer-by-Wire and Variable-rate steering systems are perhaps even more-so historically significant, but because those technologies represent state-of-the-art related to this research, they are reviewed in the next section.

The State-of-the-Art in Steering Systems

Electronic Stability Control (ESC) systems currently represent an important segment of the state-of–the-art in steering systems not incorporating steer-by-wire. ESC analyzes information from vehicle sensors and corrects driver input to increase stability by limiting or decreasing vehicle speed and/or acceleration during maneuvers that would otherwise exceed the vehicle's handling limits.

The National Highway Traffic Safety Administration (NHTSA) has concluded that ESC appears to be highly effective in reducing single vehicle run-off-road crashes such as rollovers and collisions with fixed objects (Dang, 2004). It is important to note that ESC in non-steer-by-wire vehicles stabilizes vehicle yaw and traction through throttle and braking alone—there is no adjustment made to the driver's steering input. Even so, vehicles with ESC in the United States have had a single-vehicle crash risk that is 41 percent lower than vehicles without ESC, which suggests that approximately 800,000 of the 2,000,000 single-vehicle crashes that occur in the US might be avoided if all vehicles were equipped with ESC (Farmer, 2004).

As part of a steer-by-wire platform, ESC could be enhanced by intervening on the driver's steering input to more-smoothly alter the vehicle's course while preserving both safety and vehicle performance (Yih et al., 2005). Yih goes on to describe the sensation of "connectedness" between engaging the steering wheel and feeling the response of the road wheels. A force-feedback system to accommodate such communication back to the driver would be a mandatory component of a final system—playing a pivotal role in consumer acceptance. Even though the framework presented in this research could accommodate this level of force-feedback within the simulation, it is not explored or evaluated as part of the variable ratio steering that will be utilized as part of this research.

Variable-rate steering systems were originally designed as purely mechanical devices that implemented a progressively higher rate of steering toward the steering-wheel ends, relative to the rate at steering-wheel center. This is intended to provide quicker vehicle response, but the overall function is not adaptable to vehicle speed (Bishop, 1973). More-recent nonlinear (variable ratio) steering systems are typically variations of the Bavarian Motor Works' (BMW) Active Steering (BMW AG, Munich, Germany) (Kuehnhoefer & Biegert, 2007; Kumar & Kamble, 2012) or Audi's Dynamic Steering (Audi AG, Ingolstadt, Germany), which aims to reduce the number of steering-wheel turns from the conventional two-and-a-half turn, to less than two turns in low-speed/parking-lot situations (Koehn & Eckrich, 2004). These systems implement steering wheel actual input, driving a combination of planetary gears and an electric motor to synthesize the effective steering input, as illustrated in Figure 2.1. The mechanical output from the gear and motor system in turn engages a standard (power-assisted) rack and pinion gear to steer the front road wheels.

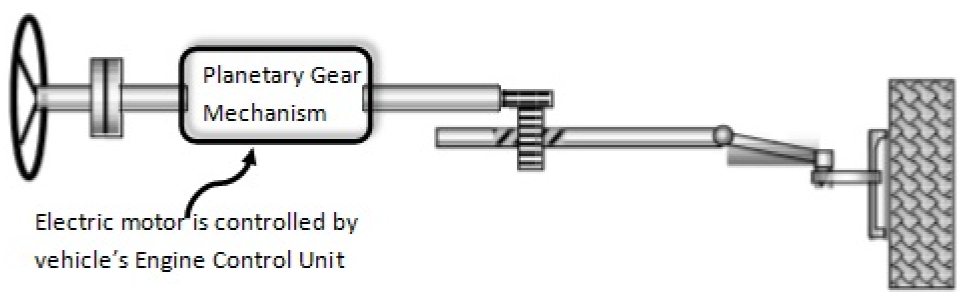

Figure 2.1: Conceptual mechanical nonlinear steering configuration

The steering wheel rotation is coupled to an drive gear at the end of the input steering column (known as a sun gear), which is translated to an output sun gear at a net 1:1 ratio coupled to the output steering column. A set of planetary gears, each of two pairs connected with a common lay shaft, engage the sun gears to a common geared, rotatable housing. This in turn engages with the electric motor. The electric motor is controlled by the vehicle's Engine Control Unit (ECU), which ultimately varies the effective steering ratio. This configuration is illustrated in Figure 2.2 on page 14. Fault tolerance in this design consists of locking the rotatable housing, which results in a fixed 1:1 steering ratio.

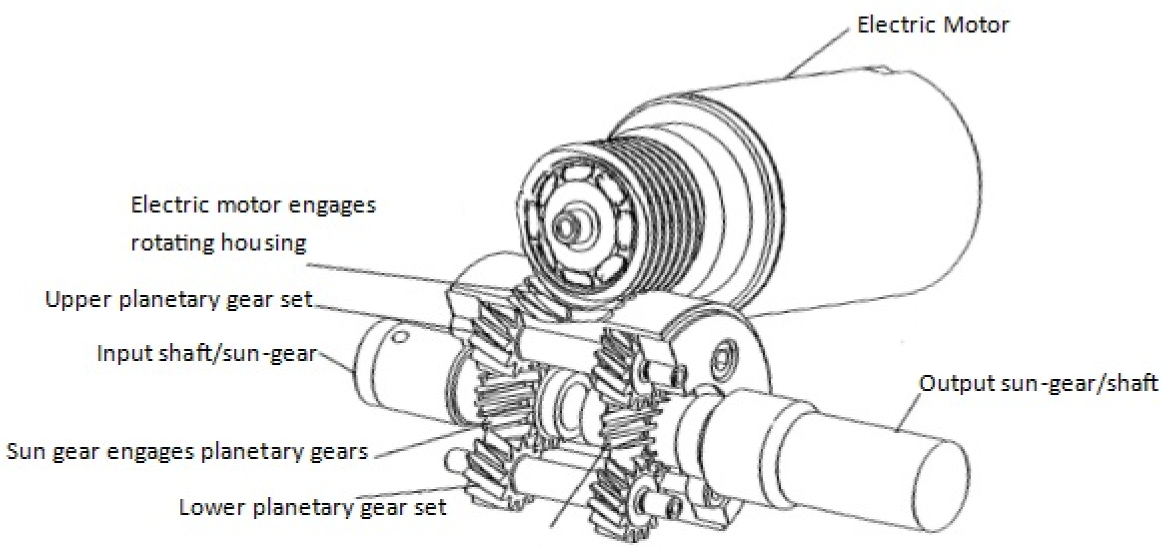

Figure 2.2: BMW Active Steering configuration

Ford (Ford Motor Company, Dearborn, Michigan, U.S.) in conjunction with the automotive components supplier Takata (Takata Corporation, Tokyo, Japan) has announced Ford Adaptive Steering, which is described to accomplish the same variable-ratio steering as with the BMW and Audi systems—however, the entire mechanism is to be contained within the vehicle's steering wheel hub.

Another vehicle employing steer-by-wire technology is the Mercedes-Benz multipurpose auto-four-wheel-drive truck called the Unimog—even though it is presently considered a concept vehicle, it received German "Straßenzulassung" (road legal) approval for a Steer-by-Wire system (Schmitt, 2011).

Safety Considerations in x-by-Wire Systems

Knight (2002) predicted the need for advances in specification, architecture, verification and process where safety-critical systems are being developed. We are already seeing a dramatic increase in the number of safety-critical systems that are computer controlled, which are replacing more conventional mechanical systems. Robotic surgeries, from ophthalmic procedures to the da Vinci surgical robot (Intuitive Surgical, Inc., Sunnyvale, CA), is one example. Safety-critical by-wire control in both military and commercial aircraft is also pointed out by Knight.

Drive-by-wire systems, in general, can be designed and implemented in two ways: with mechanical backup, or without mechanical backup.

Because a main objective of this testing framework is to enable a steering system that replaces conventional purely-mechanical methods with electrical signals over wire (or other transmission medium, for that matter, e.g. fiber optics), it is necessary and prudent to mention safety options, including redundancy and fault tolerance. Dunn (2003) explains that, despite the scope and ubiquity of computer control of mechanical systems (not limited to steer-by-wire controls, but also including safety-critical applications that touch most of us: life-support systems, automated air- and surface-traffic control, and so on), they commonly fail for reasons that can be classified in one of the following three categories: Designers or users i. "have an incomplete understanding of what makes a system 'safe'"; ii. "fail to consider the larger system into which the implemented concept is to be embedded,"; iii. "ignore single points of failure that will make the safe concept unsafe when put into practice." Generally speaking, this view of fault possibilities is inclusive of an entire control system. In the specific implementation of a steer-by-wire steering system, the system can be separated into three subsystems—any one of which can lead to loss of steering. These are the Actuator, Controller, and Sensor subsystems, shown in Figure 2.3 on page 16, along with an illustration of how a fault in any of the subsystems can result in loss of steering. The Sensor and Actuator subsystems, respectively, report the position of the road wheels (in addition to other sensors, if so designed) and set their steering angle according to the output of the Control subsystem.

Although production of steer-by-wire vehicles is currently very limited, Isermann, Schwarz & Stölzl (2002) point out the increasing demand and address the hazard severity in designing and delivering safe drive-by-wire systems overall. Their work outlines schemes for safety/hazard analysis and fault-tolerant design, as well as considerations for implementing redundant systems. These principles would be applied at the level of an overall x-by-wire system design.

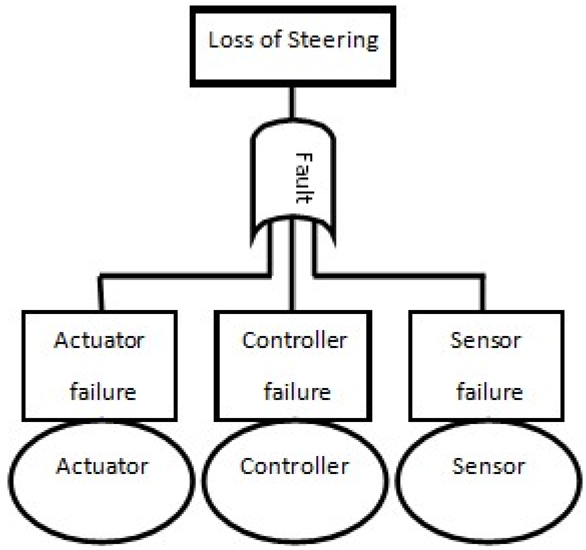

Figure 2.3: Conceptual steer-by-wire fault tree

The framework being presented herein focuses specifically on the Control subsystem as further illustrated in Figure 2.4. The design of the steering system being implemented as part of this experiment also collects and utilizes the vehicle's velocity from its ECU (through simulation), but could incorporate input from real-time sensors (e.g. road wheel angle, accelerometer, vehicle tip/rotation, etc.), as well as haptic feedback to the steering wheel.

Amberkar, D'Ambrosio, Murray, Wysocki & Czerny (2000) present a general hazard analysis process for x-by-wire systems that are safety-critical systems. The process is summarized in the following 16 steps:

1. Cause-Consequence Analysis
2. Common Cause Analysis
3. Electromagnetic Compatibility Analysis and Testing

4. Event Tree Analysis
5. Failure Modes and Effects Analysis
6. Failure Modes, Effects, and Criticality Analysis
7. Fault Tree Analysis
8. Hazard and Operability Study Hardware/Software Safety Analysis
9. Modeling
10. Root Cause Analysis
11. Safety Review
12. Sneak-Circuit Analysis
13. Software Failure Modes and Effects Analysis
14. Software Fault Tree Analysis
15. Software Hazard Analysis
16. Software Sneak Circuit Analysis

The framework presented as part of this experiment is designed as a subsystem. It is intended to be incorporated as a component of an overall steer-by-wire design and test system that would support such a hazard/safety analysis process.

There are currently a few consumer passenger vehicles commercially available with purely Steer-by-Wire (SBW) steering systems. A notable example is Nissan's (Nissan, Yokohama, Japan) Infinity Q50. The Q50 employs an electronic connection, with no physical connection between the steering wheel and the road wheels. The SBW consists of a computer controller, clutch, and steering-angle actuator to translate the driver's input from the steering wheel to the road wheels. Similar to the BMW system, the Q50 employs variable degrees of power-assist and steering ratio to suit the steering event (Ulrich, 2013). To address fault tolerance, Nissan has designed this steering system with three independent controllers to maintain a practical level of passenger safety. Nissan also claims a unique feature (by eliminating the mechanical steering connection), which is the ability to filter out road feedback such as rough-road vibrations and impacts that are normally transmitted through the vehicle's steering column.

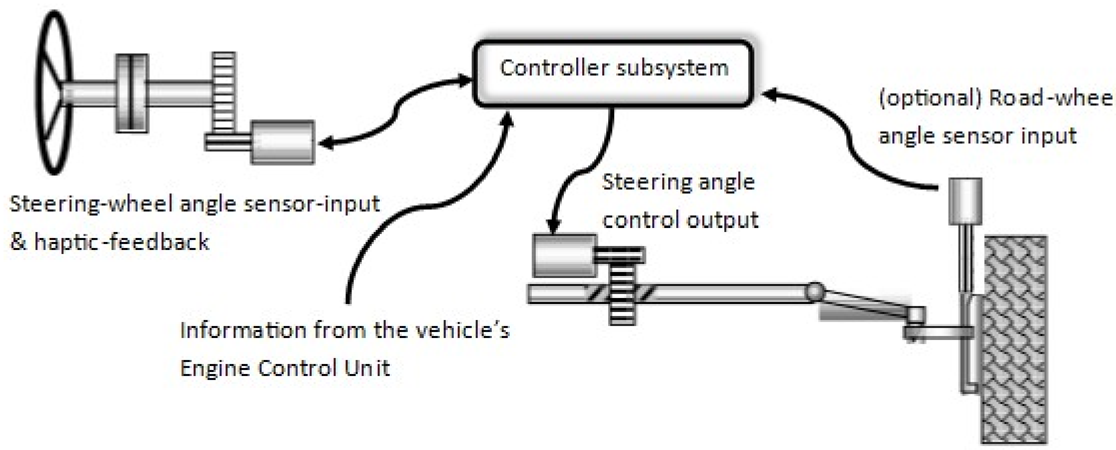

Figure 2.4: Conceptual steer-by-wire subsystem

In addition to canceling the effects of road disturbance forces, Yih, Ryu & Gerdes (2005) have experimentally verified key improvements to SBW systems by leveraging inputs from Global Positioning Systems (GPS) and Inertial Navigation System (INS) sensors located in the vehicle. Their methodology seeks to adjust-for and minimize oversteer or understeer based on indications of vehicle yaw-rate and side-slip.

Zheng, Altemare & Anwar (2005) describe a fault tolerant steer-by-wire methodology using a dual motor, dual microcontroller architecture. One of the pair of microcontrollers serves as the master, while the other stands by to provide redundancy. The twin actuating motors work in unison to share the torque used in steering the road wheels. If one fails, the system automatically switches to single motor operation.

A Human Factors Approach to (Steering System) Design Requirements

Human Anatomical Constraints

Every driver explicitly and/or intuitively realizes that an n-degree angular displacement of a steering over a given moment in time has a greater and greater effect as vehicle speed increases. For example, a 15° deflection of a steering wheel for one second at 70 m.p.h. has a markedly greater effect on a vehicle's path than the same maneuver at 10 m.p.h. There exists a non-proportionality of steering input effect across the range of a vehicle's velocity. A driver must be cognizant of the discordance between steering input and vehicle response at varying speeds if he or she is to predict the results of his or her steering inputs at various speeds. A relevant example would be over-correction, defined as excessive steering input in response to a panic reaction causing the driver to lose control of the vehicle, which is more likely to occur as vehicle velocity increases (Spainhour & Mishra, 2008).

At higher speeds, if a driver encounters an emergent situation requiring quick hand-over-hand steering, he should anticipate that recovery from the maneuver (steering wheel reversal) will necessitate similar efforts in order to recover and stabilize the vehicle. The cognitive demand for the driver who has not yet developed adequate skills to negotiate the primary and secondary task demands needed to perform vehicle recovery may exceed that of a novice driver (Patten, Kircher, Östlund, Nilsson & Svenson, 2006); tracking the orientation of the steering wheel (relative to center) is compounded with the fast hand repositioning involved with hand-over-hand steering or shuffle steering. Here, the effect of associated diminished dexterity on driving safety is presumed.

Accordingly, if two-handed steering operation is to be achieved in a way that eliminates the need for removal of the hands or hand repositioning in a maneuver, the practical limits of the human body while engaged in steering must be examined. The maximum safe two-handed wheel position with respect to constraint torques on the human body is approximately 275° (Johnson, Van der Loos, Burgar, Shor & Leifer, 2003), but this does not address driver comfort or preferences. A validated skeletal model of the upper human limb was used for further biomechanical analysis (Pennestrì et al., 2007). The model is comprised of three links: the shoulder, the elbow, and the wrist, connecting to the body the following segments: the humerus, the ulna, the radius, and the hand. It is considered a seven degrees-of-freedom model within a 3-dimensional space. The practical limits of the upper limb during steering with respect to each segment's extension and prono-supination will be derived from Table 2.1. The table references an upper limb that is extended forward (anteriorly) at a right angle from the body (perpendicularly), and that is supinated upward (thumb rotated outward). The practical application of the derived limits will be verified using a diverse set of human subjects, which will be seated in the simulator hardware proposed for this experimental study.

Table 2.1: Limits for upper limb joint angles

Angle	Minimum value (degrees)(a_{min})	Maximum value (degrees)(a_{max})
a_1	-90	135
a_2	-80	45
a_3	-100	25
a_4	-140	0
a_5	-140	0
a_6	0	15
a_7	-180	0
a_8	-80	80
a_9	-25	50

The angles a_i in Table 2.1 above, are defined as follows:

a_1 as the angle of the humerus w.r.t. global Y-axis;

a_2 as the angle of the humerus w.r.t. global Z-axis;

a_3 as the angle of the humerus w.r.t. global X-axis;

a_4 as the relative angle between humerus and ulna (about humerus y-axis);

a_5 as the relative angle between radius and humerus (about humerus y-axis);

a_6 as the relative angle between radius and humerus (about humerus z-axis);

a_7 as the relative angle between radius and humerus (about humerus x-axis);

a_8 as the relative angle between hand and radius (about radius y-axis);

a_9 as the relative angle between hand and radius (about radius z-axis).

Furthermore, Lechner & Malaterre (1991) tell us that most drivers resort to braking (rather than steering) when faced with a challenging situation. Accordingly, if steering response is to be singularly studied, corresponding consideration must be given to simulator design. For example, throttle and braking control can be assigned to the simulator in order to isolate a driver's steering-response inputs.

Gender-based Bias

Gender is commonly referenced (particularly anecdotally) as a factor influencing driver performance. However, the context within which comparisons are drawn between female and male drivers when studied is historically somewhat nonspecific—and most-often examining patterns of behavior. For example, Yagil (1998) studied gender (among other demographic variables, such as youth) as a factor affecting attitudes toward the commission of driving violations. The study concludes that female drivers perceive a higher level of importance, and therefore demonstrated greater motivation to comply with traffic laws than their male counterparts. Additionally, the study reports that younger and male drivers are more-likely to demonstrate risky driving behavior; however, no direct evaluation is made with respect to physical driving skills–let alone having a focus on steering.

Holland et al. (2010) looks a little-more closely at the etiology behind the riskier behavior associated with male drivers. The resulting research concludes that women, having more external Locus of Control (LOC), are more likely to integrate experience into their perception of their own driving abilities and temper driving style accordingly. Also that males, having more internal LOC, are more likely to demonstrate unsafe driving styles due to an associated negative influence towards consideration of experience. Even though this study addresses components of driving-skill self-assessment, a comparison of physical driving skills between males and females, per se, is not directly addressed.

When Özkan & Lajunen (2006) studied driving-skill differences between women and men, he examined both self-assessment of skills and driving behavior as a function of gender. The results showed that perceptual-motor skills increased as a function of masculinity, while safety skills increased as a function of femininity. Even though driving-skills were evaluated, the scores were self-reported–not physically measured. Moreover, steering skills needed to control a vehicle were not specifically evaluated.

A month-long study conducted by the Road, Rail, and Transport section of "The Telegraph" (Agency, 2015) concludes that women are better drivers than men by scoring a combination of factors, including both behavioral and skill-based (23.6 out of 30 versus 19.8 out of 30). Contrary to the overall results, however, data from the study listed in Table 2.2 beginning on page 23 exhibited higher scores in the category of Steering—indicating that further research focused on steering ideally should account for gender-bias in the resulting performance statistics.

Table 2.2: Men vs. women driving skills

Activity	Men	Women
Appropriate speed approaching hazards	55%	75%
Stopping safely at amber traffic lights	44%	85%
Negative impact on other drivers	73%	54%
Adequate indication	82%	96%
Adequate use of mirrors	46%	79%
Effective observation	82%	71%
Driving too close to the vehicle in front	27%	4%
Staying within the speed limit	86%	89%
Appropriate speed for the situation	64%	64%
Steering / Control of the vehicle	100%	96%
Cutting corners when turning	68%	43%
Talking or texting while driving	24%	16%
Cutting dangerously in to traffic	14%	1%
Causing an obstruction on the road	25%	16%
Total co-efficient (max 30)	19.8	23.6

Standards and Practices in Automotive Testing

This research does not measure driver reaction times, nor does it monitor situational vigilance; it does, however, seek to quantify driver steering competence in comparative scenarios. Accordingly, the testing scenarios will be oriented towards the type(s) of testing that is prevalent in the automotive industry to evaluate vehicle steering.

Smith & Sommerfeld (2011) explain that, whereas a slalom test is a de facto standard for testing steering characteristics, there is no standard interval between stanchions (gates) or number of gates that should be negotiated in a trial. He goes on to reveal that the testing at HotRod Network is conducted with seven gates spaced at 70-foot intervals on a 420 foot course.

Elfalan (2009) describes the slalom testing at Road & Track as a relatively higher-speed test consisting of eight gates at 100-foot intervals on a 700 foot course. Additionally, he explains that a managed entry speed is crucial to meaningful results.

In a study similar to this one, Andonian et al. (2003) compares conventional steering with a joystick controlled steering system. The parameters of Andonian's slalom testing defined 50-meter intervals at a speed of 60 mph (Andonian et al., 2003). This interval contrasts the minimal legal interval specified by the Sports Car Club of America (SCCA) for stanchion positioning in an autocross slalom event. The SCCA Solo Rulebook specifies a minimum distance of 45 feet between stanchions and a minimum track width of 15 feet, although a more practical guideline that is generally observed is 20 paces, or 60 feet between stanchions (Sports Car Club of America, 2015).

In validating a simulator to study vehicle rollover prevention using a virtual test track, Yoon et al. (2010) used a constant vehicle speed of about 37 mph on a slalom course with cones spaced about 98 feet apart. His team found that comparing lateral accelerations using these metrics was within the feasible range for validation. In an experiment designed to study the maneuverability of cars controlled by joysticks, Östlund & Peters (2000) achieved results using stanchion intervals of about 38 feet.

Given these findings, the range of stanchion intervals used in vehicle control studies and automotive testing appears quite broad, ranging from 38 to 100 feet. As a starting point, a middle-of-the-road value of 50 feet (15.24 meters) was implemented as the interval value for experimentation.

In addition to number of gates and the interval lengths separating them, there also needs to be consideration given to the lane width of the track itself. If the sinusoidal path driven in a slalom course is viewed as alternating lane changes, one can conclude a course width of twice the lane width of a conventional roadway. The Federal Highway Administration specifies an overall width criterion (in urban as well rural locales) for local roads and freeways, including entrance collectors and exit ways to be 12 feet (American Association of State Highway and Transportation Officials

(AASHTO), 2011). Accordingly, this experiment will initially implement a 24-foot wide track for the slalom course in this experiment.

Hardware and Open-source Modeling, Simulation, and Graphics Software

In designing a simulator to study steering characteristics of a new steering system, as well as the effect upon drivers who would use it, the efficacy of simulator is paramount. This begins with the simulator software. Given the budgetary limitations of this research (unfunded), the preferred domain for software selection included only Open Source Definition (OSD) licensing (Lee, 1999). One simulator software package fitting this criterion and licensed under General Public License (GPL) is The Open Car Racing Simulator (TORCS), an open-source, 3D, multi-platform driving simulator based on the OpenGL graphics library (Wymann et al., 2004, 2015) and its more-recent development fork, Speed Dreams (SD) (Gaëtan et al., 2012). The combination of TORCS/SD with commercial off-the-shelf hardware provides a research and development platform that is financially manageable while delivering the flexibility and function needed to design and implement a suitable simulator (Charissis & Papanastasiou, 2008).

As of 2013, over 300 research papers have been written using TORCS as a driving simulation platform (Wymann et al., 2015). For example, Ali et al. (2013) develop a control law model for stably platooning vehicles on a highway one meter apart using TORCS. They cite three reasons for the choice of simulation software: 1) A sophisticated physics engine (aerodynamics, traction, fuel consumption, etc.) coupled with a 3D graphics engine for visualization; 2) The software is provided as C++ source code and is designed to allow development of custom controllers; 3) TORCS blends a fully customizable research-quality environment with the sophistication of commercial car racing games. In a different study, Doshi & Trivedi (2010) examined indicators of driver style on a TORCS based simulator to test the predictability and responsiveness or drivers in the real world. TORCS allowed researchers to set the complexity of the scenario and collect data for subsequent analysis of driver dynamics. Table 2.3 shows a partial listing of published studies, experiments, and reports where TORCS/Speed Dreams had been used as the driving simulator.

Table 2.3: Listing TORCS/Speed Dreams Citations

Title	Author, (Year)	Ct
A Control-Theoretic Approach to Adaptive Physiological Games	Parnandi et al. (2013)	10
A Novel Virtual Reality Driving Environment for Autism Intervention	Bian et al. (2013)	9
An Experimental Space for Conducting Controlled Driving Behavior Studies Based on a Multiuser Networked 3D Virtual Environment and the Scenario Markup Language	Gajananan et al. (2013)	11
Design of a Virtual Reality Driving Environment to Assess Performance of Teenagers with ASD	Wade et al. (2014)	6
Evaluating Multimodal Driver Displays of Varying Urgency	Politis et al. (2013)	14
Experimental Study of Steer-By-Wire Ratios and Response Curves in a Simulated High Speed Vehicle	Marks & Wellington (2013)	8
Facelight: Potentials and Drawbacks of Thermal Imaging to Infer Driver Stress	Anzengruber & Riener (2012)	1
Fatigue Driving Detection System Design Based on Driving Behavior	Hailin et al. (2010)	8
Gesturing on the Steering Wheel: A User-Elicited Taxonomy	Angelini et al. (2014)	3
Investigation of Cooperative Driving Behaviour During Lane Change in a Multi-Driver Simulation Environment	Heesen et al. (2012)	13
Multi-User Blood Alcohol Content Estimation in a Realistic Simulator using Artificial Neural Networks and Support Vector Machines	Robinel & Puzenat (2013)	3
OpenEnergySim: A 3D Internet Based Experimental Framework for Integrating Traffic Simulation and Multi-User Immersive Driving	Nakasone et al. (2011)	12
Optic Flow Asymmetries Bias High-Speed Steering Along Roads	Kountouriotis et al. (2013)	6
Preferred or Adopted Time Headway? A Driving Simulator Study	Gouy et al. (2013)	2

Title	Author, (Year)	Ct
Real Time Drunkenness Analysis in a Realistic Car Simulation	Robinel & Puzenat (2012)	2
Specification of Test Procedures for the Simulator Experiments	Barnard et al. (2010)	3
SpeeT: A Multimodal interaction Style Combining Speech and Touch Interaction in Automotive Environments	Pfleging et al. (2011)	7
Supporting Drivers in Concurrent Lane and Speed Tracking Tasks with Novel Visual, Auditory, and Tactile Speedometer Displays	Yang et al. (2013)	2
Temporal Multimodal Data Synchronisation for the Analysis of a Game Driving Task using EEG	Sivanathan et al. (2014)	1
Using an OpenDS Driving Simulator for Car Following: A First Attempt	Green et al. (2014)	1

The Logitech G27 (Logitech G27, Logitech, Fremont, CA) steering wheel and pedal board combination is commonly used to control PC-based simulators. Table 2.3 shows a partial listing of published studies, experiments, and reports where the Logitech G27 set was used to control a driving simulator.

Table 2.3: Listing Logitech G27 Citations

Title	Author, (Year)	Ct
A Control-Theoretic Approach to Adaptive Physiological Games	Parnandi et al. (2013)	10
A Novel Virtual Reality Driving Environment for Autism Intervention	Bian et al. (2013)	9
An Experimental Space for Conducting Controlled Driving Behavior Studies Based on a Multiuser Networked 3D Virtual Environment and the Scenario Markup Language	Gajananan et al. (2013)	11
Design of a Virtual Reality Driving Environment to Assess Performance of Teenagers with ASD	Wade et al. (2014)	6

Title	Author, (Year)	Ct
Evaluating Multimodal Driver Displays of Varying Urgency	Politis et al. (2013)	14
Experimental Study of Steer-By-Wire Ratios and Response Curves in a Simulated High Speed Vehicle	Marks & Wellington (2013)	8
Facelight: Potentials and Drawbacks of Thermal Imaging to Infer Driver Stress	Anzengruber & Riener (2012)	1
Fatigue Driving Detection System Design Based on Driving Behavior	Hailin et al. (2010)	8
Gesturing on the Steering Wheel: A User-Elicited Taxonomy	Angelini et al. (2014)	3
investigation of Cooperative Driving Behaviour During Lane Change in a Multi-Driver Simulation Environment	Heesen et al. (2012)	13
Multi-User Blood Alcohol Content Estimation in a Realistic Simulator using Artificial Neural Networks and Support Vector Machines	Robinel & Puzenat (2013)	3
OpenEnergySim: A 3D Internet Based Experimental Framework for Integrating Traffic Simulation and Multi-User Immersive Driving	Nakasone et al. (2011)	12
Optic Flow Asymmetries Bias High-Speed Steering Along Roads	Kountouriotis et al. (2013)	6
Preferred or Adopted Time Headway? A Driving Simulator Study	Gouy et al. (2013)	2
Real Time Drunkenness Analysis in a Realistic Car Simulation	Robinel & Puzenat (2012)	2
Specification of Test Procedures for the Simulator Experiments	Barnard et al. (2010)	3
SpeeT: A Multimodal interaction Style Combining Speech and Touch Interaction in Automotive Environments	Pfleging et al. (2011)	7
Supporting Drivers in Concurrent Lane and Speed Tracking Tasks with Novel Visual, Auditory, and Tactile Speedometer Displays	Yang et al. (2013)	2
Temporal Multimodal Data Synchronisation for the Analysis of a Game Driving Task using EEG	Sivanathan et al. (2014)	1
Using an OpenDS Driving Simulator for Car Following: A 1st Attempt	Green et al. (2014)	1

Epic Games (Epic Games, Inc., 1991) Unreal Engine 4 (2014) is a VR physics and rendering platform used widely in academia, as well as in the retail computer gaming industry (Batchelor, 2014).

In the months following the initial development of a custom simulator with which to present driving test vignettes for this research, Epic Games updated their end-user license agreement (EULA, 2017) such that source code and usage rights would be provided by Epic, and could be used within the scope of this research free of cost (Matulef, 2014). This policy change occurred during the Fall of 2015 and Oculus Rift licensing/integration was included during the latter part of 2016 (Graft, 2016). This licensing made the integration of Epic's Unreal Engine 4 into the experimental driving simulator a very practical solution. Hence it was included as a development tool for this study to provide Oculus 3D rendering and PhysX Engine support to present the final VR testing vignettes as an ultimate replacement for the TORCS/SpeedDreams prototyping.

Prior to Epic's pricing policy change to a general distribution of Unreal Engine 4, only select universities were granted licenses to develop projects free of charge—all others being subjected a monthly subscription fee (Nutt, 2015; Sweeney, 2015).

Table 2.4 shows a partial listing of published studies, experiments, and reports where Epic Games, Inc. Unreal Engine 4 had been used as the development platform to generate the physics and visual rendering for driving simulation dynamics or other virtual or augmented reality applications requiring accurate simulation of real-world physics.

Table 2.4: Listing Unreal/PhysX Citations

Title	Author, (Year)	Ct
A framework for game engine selection for gamification and serious games	(Ali & Usman, 2016)	
A Game-Engine-Based Platform for Modeling and Computing Artificial Transportation Systems	(Miao et al., 2011)	35

Title	Author, (Year0	Ct
A Multifunctional VR-Simulator Platform for the Evaluation of Automotive User Interfaces	(Poitschke et al., 2007)	7
A realistic reaction system for modern video games	(Gruenwoldt et al., 2005)	7
A Survey of Commercial & Open Source Unmanned Vehicle Simulators	(Craighead et al., 2007)	165
A virtual reality platform for safe evaluation and training of natural gaze-based wheelchair driving	(Ktena et al., 2015)	8
An experimental testbed to enable autodynamic difficulty in modern video games	(Bailey & Katchabaw, 2005)	34
An Integrated Architecture for Autonomous Vehicles Simulation	(Pereira & Rossetti, 2012)	25
An overview of training simulation research and systems	(Barles et al., 2005)	7
ARGoS: A modular, multi-engine simulator for heterogeneous swarm robotics	(Pinciroli et al., 2011)	101
Behavioural Research in an Advanced Driving Simulator - Experiences of the VTI System	(Nilsson, 1993)	85
Creating 3D Virtual Driving Environments for Simulation-Aided Development of Autonomous Driving and Active Safety	(Jayaraman et al., 2017)	
Development of a Virtual Electric Wheelchair-Simulation and Assessment of Physical Fidelity Using the Unreal Engine 3	(Herrlich et al., 2010)	3
Human-robot teaming for search and rescue	(Nourbakhsh et al., 2005)	211
Intelligent wheelchair simulation: Requirements and arch. issues	(Petry et al., 2011)	14
Mobility open architecture simulation and tools environment	(Balakirsky et al., 2005)	13
OpenEnergySim: A 3D Internet Based Experimental Framework for Integrating Traffic Simulation and Multi-user Immersive Driving	(Nakasone et al., 2011)	15

Title	Author, (Year0	Ct
Robot simulation physics validation	(Pepper et al., 2007)	80
Towards quantitative comparisons of robot algorithms: Experiences with SLAM in simulation and real world systems	(Balaguer et al., 2007)	29
UnrealCV: Connecting Computer Vision to Unreal Engine	(Qiu & Yuille, 2016)	10
Using the PhysX engine for physics-based virtual surgery with force feedback	(Maciel et al., 2009)	77
Virtual reality for mine safety training	(Filigenzi et al., 2000)	39
A survey on position-based simulation methods in computer graphics	(Bender et al., 2014)	52
Cuda fluid simulation in nvidia physx	(Harris, 2009)	9

Identifying the Gap in Current Research

A review of literature describing past and current research associated with automotive steering system development relevant to this topic reveals gaps in the published body of knowledge, and therefore justifies further study. The following chapter describes the experimental methodology used to address the research gaps motivating this study, the research questions predicated on the gaps, the hypotheses derived to examine (and ultimately answer) the questions, and the research framework by which the hypotheses were ultimately tested.

In Academia, the fast-growing number of researchers, coupled with the lack of common research and development frameworks has resulted in an increase of concerns regarding design research effectiveness and efficiency (Blessing & others, 2003). Blessing goes on to emphasize the importance of establishing methodology that both studies the phenomenon of design as well as supporting the design itself to improve research. Similarly, a research-framework void exists with respect to a common framework oriented to the development of automotive steering systems, as well as a means by which to assess the impact of a product steering controller on driver performance. More specifically, are the current paradigms ideal or even sufficient for adaptation in newer-technology steering? Would people drive better, or even show preferences between the conventional and, perhaps, a system that resolves unnecessary steering-wheel manipulation?

Whereas state-of-the-art consumer automobile steering systems exist today that reduce the number of steering-wheel rotations (with a variable steering ratio) needed to operate the vehicles in which they are installed, none resolve the problem of having to alternately remove one hand and then the other to shuffle-steer or to steer with hand-over-hand motions. Also, there is no design framework (meeting the requirements described above) available that can be set up in any academic or other research facility as a de facto standard for developing the theories and implementation of steering controllers, easily and inexpensively.

Given the task of designing a steering controller that will translate a reduced steering wheel rotational travel (e.g. 225° lock-to-lock) to practical road-wheel actuation under a variety of conditions, the availability of such a design framework would be ideal. It would be most desirable that the framework would be comprised of sophisticated and modifiable software components that have been validated and freely available under public licensing such as the GNU General Public License (GNU or GPL, www.gnu.org/licenses/gpl.html), as well as Commercially Off The Shelf (COTS) hardware. For the purposes of this study, the framework must also support a customized track or Synthetic Environment (SE) with collision detection and other SE sensors with which to observe and measure the moments and events needed to study a steering control design. Moreover, given the limits of display monitors in a 360°-view environment (Stevens, 2014), incorporation of a head-mounted Virtual Reality (VR) device such as an Oculus Rift (Oculus VR, LLC, Menlo Park, CA, U.S.A.) would be preferred for this study.

The research and design proposed herein is an effort to coadunate the design of a steering-control method with the development of a novel driving simulator upon which to test it. The former is intended as a contribution to the body of scientific data related to driver control of adaptable steering systems within the automotive industry. The latter is being positioned for more-general application to the body of work and customization of driving simulators in VR—specifically toward Academia. Collectively, this work creates a research framework within which new steer-by-wire steering systems can be evaluated for effectiveness and adoptability.

CHAPTER 3: EXPERIMENTAL METHOD

Overview of Methodology

Consequent to the review of literature presented in the preceding chapter, four research questions were derived by which to further study a framework-design oriented toward developing novel steering systems. From these questions, four hypothetical answers were formulated and studied for validity through experimentation and statistical analysis. The following research methodology restates the four questions, associates each of them with a corresponding hypothesis and method of validation as research objectives, and finally describes in detail the execution of the study as it relates to testing the hypotheses.

Research Objectives

Question 1

Will a multivariate steering-rate vehicle control system, which will allow a driver (i.e. study participant) to maintain uninterrupted hand positioning on a steering wheel during any steering maneuver measurably affect driver performance?

The hypothesis formulated for the study of the first research question follows:

Hypothesis 1: Drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.

Method by which to Test Hypothesis 1

The first hypothesis was tested using a novel simulator designed to score driver performance during prescribed steering maneuvers. The resulting scores were evaluated by way of repeated measures statistical testing using the Wilcoxon Signed Rank Test (Wilcoxon et al., 1963) due to non-parametric data distribution. Details of the findings are described in the next chapter.

Question 2

Will a multivariate steering-rate vehicle control system, which will allow a driver (i.e. study participant) to maintain uninterrupted hand positioning on a steering wheel during any steering maneuver be preferred by drivers?

The hypothesis formulated for the study of the second research question follows:

Hypothesis 2: Drivers in a simulated environment will prefer using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.

Method by which to Test Hypothesis 2

The second hypothesis was tested using a survey document, specifically an adapted version of the Mouloua Usability Survey (Rivera et al., 2010). The questionnaire results were evaluated using an analysis of variance statistical test. Details of the findings are described in the next chapter.

Question 3

Compared with study participants' respective performance driving a conventional steering system (in simulation) versus a multivariate steering-rate vehicle control system designed for the purposes of this research, will gender be a factor to a statistical significance?

The hypothesis formulated for the study of the third research question follows on the next page:

Hypothesis 3: Male drivers in a simulated environment will perform no differently from female drivers at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control.

Method by which to Test Hypothesis 3

The same simulator scores used to test Hypothesis 1 were used to differentiate performance by gender. A Mann-Whitney U Test (Mann & Whitney, 1947) was employed as a non-parametric alternative to an independent-samples t-test. Details of the findings are described in the next chapter.

Question 4

Compared with participants' respective performance driving a conventional steering system (in simulation) versus a multivariate steering-rate vehicle control system designed for the purposes of this research, will age be a factor to a statistical significance?

The hypothesis formulated for the study of the fourth research question follows:

Hypothesis 4: Younger drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control than older drivers.

Method by which to Test Hypothesis 4

Again, the same simulator scores used to test Hypothesis 1 were used, but to differentiate performance by age. Similarly, a Mann-Whitney U Test was employed as a non-parametric alternative to an independent-samples t-test. Details of the findings are described in the next chapter.

The Role of Simulation

The use of simulation techniques are indicated in this study because of practical implications (e.g. development time, financial expense, technical challenges, etc.).

Simulation Objectives

The design of this driving simulator involved a two-tiered conceptual approach. The base tier defines the development and standardization of a novel driving simulator upon which to test modular steering design systems. Design parameters must specifically include mapping of steering-wheel input to the output that sets the drive-wheel steering angle. The parameters must also account for vehicle velocity and angular speed of steering-wheel deflection. Finally, performance must be measurable.

The second (specialization) tier defines the development of a steering control designed to enable effective operation of a vehicle without interrupting the driver's two-handed control (shuffling or removing either hand during steering maneuvers). Also because some driving maneuvers require greater steering efforts—such as parallel parking—a driver may need to turn his or her head to see to the rear and/or to the side. Therefore, 360° visual perception (as opposed to a single or multiple monitor screens placed before a front-facing driver) was considered optimal and implemented into the design. Furthermore, if the platform needs to be reasonably affordable and apply to a wide range of research aims, the use of open-sourced software and COTS hardware, including VR technology, could accelerate the construction and operation of a specialized driving simulator. A well-designed, standardized solution framework reduces or eliminates the need for, and acquisition of, multiple simulation tools across similar research and development efforts.

Both operator-performance and preferences were measured and analyzed as experimental data in order to determine results. Performance was graded using a custom driving simulator on a closed track having equally-spaced stanchions placed in a slalom configuration. The vehicle velocity was controlled by the simulation, leaving the steering as the driver's only input.

Operator/driver preferences were graded according to responses obtained from a five-point Likert-scale questionnaire, namely, a modified version of the Mouloua Usability Questionnaire (Rivera et al., 2010). The questionnaire assessed two major components of acceptance: Usefulness and Satisfaction (Lund, 2001). Performance scores were derived from a measure of collisions (with stanchions), vehicle rollovers (if they occurred), and time to complete.

Conceptual Framework

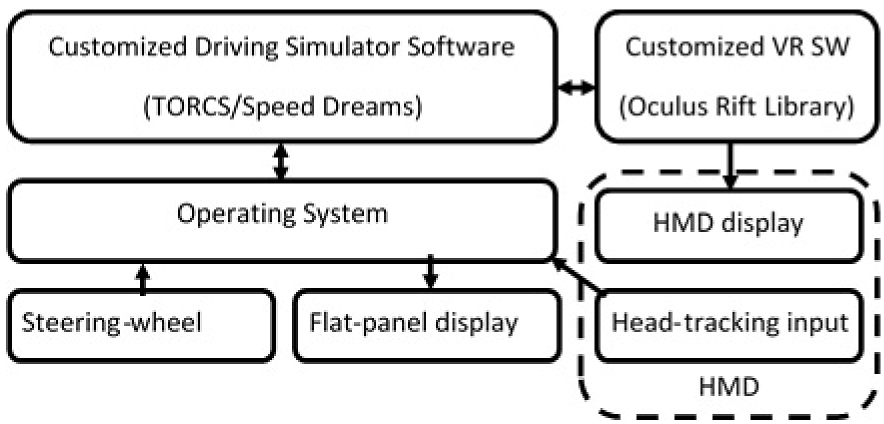

Figure 3.1: Block diagram of the research framework

Research and Design Objectives

The design objective was to build a simulator that would integrate open-sourced software, COTS hardware, 3D VR for 360° visibility, and the ability to modularly "plug in" and test various steering parameters, which could then be further developed and validated. The block diagram shown in Figure 3.1 illustrates the architectural concept.

The selected simulation software was compiled and installed in a Microsoft Windows 10 environment. The simulation software was additionally modified to support an Oculus Rift VR device for a 360° field of view, and collision detection was extended to score the number of stanchions (traffic cones) contacted during the experiment as a way to assess driver performance. A custom track upon which stanchions were placed to form slalom-course gates was also developed for this experiment.

Expected Experimental Results

The experimental results were expected to align with the four hypotheses. The first hypothesis, H1: "Drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.", was an objective measure and would be true if-and-only-if participants scored accordingly and to a statistical certainty. The second hypothesis, H2: "Drivers in a simulated environment will prefer using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.", was subjectively measured using survey instruments. Finally, results from testing hypotheses H3 and H4 were similarly objective measures based on scoring performance, also expected to align with their respective hypotheses.

Participants

The participants consisted of 54 licensed drivers, 27 of which were female and 27 of which were male. The minimum sample size (N = 23) was derived through the use of G*Power statistical software using the parameters shown in Table 3.1 below.

Table 3.1: G*Power Bivariate normal model correlation

Input variable	Value
Type of power analysis:	A priori
Tail(s):	1
Correlation: ρ H1	0.5
α err prob:	0.05
Power (1 - β err prob):	0.80
Correlation ρ H0:	0

The participants were solicited and scheduled using the University of Central Florida (UCF) Psychology Department's Sona-Systems (2002) registration system in conjunction with the UCF Institute for Simulation & Training's (IST) Sona-Systems registration system. Students who participated in this way fullled an academic requirement and were compensated monetarily at the rate of 10 USD per hour. Participants were also solicited through email sent to the IST email distribution lists.

Inclusion/Exclusion Criteria

The following three criteria were required for participation in this experiment:

1. Participants must be currently-licensed motor vehicle operators
2. Participants have normal or corrected to normal vision
3. Participants must have no previous history of seizures

Participants were additionally informed that if they exhibited any signs of simulator sickness, the participant would be dismissed from the study. Examples of simulator sickness include General Discomfort, Fatigue, Headache, Eye Strain, etc. Also, participants were informed that participation was voluntary and that they could choose to withdraw from the experiment at any time. Participants who would withdraw from the experiment or who would otherwise be deemed ineligible would receive credit based on the time participated.

Data Management

Performance data were logged using a software program designed for the experiment. The data were collected in a folder on the computer with password protection. When data collection was completed, the data were backed-up onto a secure hard-drive.

The subjective data, which were administered using paper-based surveys, were transferred to the computer and protected by a password. Data from the computer-based measures were backed-up onto a secure hard-drive that is not accessible to the public. To maintain confidentiality, a numerical code was assigned to the performance and subjective data for each participant.

Apparatus

Overview

The foremost requirement for a driving simulator that could be used for these experiments was that it would be open-sourced. In that way, steering inputs, display outputs, and physics simulation could be customized to suit the experimental needs. The software design also needed to be modular. That is, as requirements change, a component of the overall design could be modified or even exchanged for one that better accommodates the simulation or testing environment. In addition to the simulation behavior, the models for vehicles and tracks also needed to be modifiable/customizable in order to create test scenarios as required. The open-source software selected met these requirements, but was found to be limited in terms of its display capabilities. The simulator needed to support a stereoscopic VR head-mounted display (HMD) in order to present an immersive and interactive virtual 3D environment. Witmer & Singer (1998) define immersion this way, “Immersion is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences.”

The TORCS/Speed Dreams software platform (Wymann et al., 2015) was initially selected because it is open-sourced, and could be modified to support the VR requirement. Moreover, adequate support was available through forums and developer mailing lists, and the principal individuals who would participate in the development effort expressed interest. The first iteration of this design platform was employed to create test track dimensions that would reasonably, realistically, and measurably challenge driver performance with respect to operating two distinct steering systems.

The TORCS/SpeedDreams simulation platform has been widely used in academic research because it is open-sourced (primarily C++), has sufficient physics-engine options, and provides access to a level of function directly applicable to this research. The four key areas of the simulation software that were to be modified were the steering function, 3D VR support, a customized vehicle model, and a closed track interspersed with obstacles through which the test subjects operated the vehicle (either modified with the variable-rate steering function or left stock). The obstacles (stanchions/cones) would have full collision-detection interaction with the vehicles, which were linked to each test subject's performance score.

Most of the initial track design and steering system formulation was done using the combination of TORCS/Speed Dreams integrated with a graphics library that would support the Oculus Rift VR device. However, over time, the development track of TORCS/Speed Dreams and that of the graphics library OpenSceneGraph (Callejo et al., 2010) diverged in such a way that integration of the two was no longer possible. Because of the modular architecture, suitable software replacements, which became available at an opportune time, were integrated and the result was a working driving simulator with a customizable steering controller.

In the final system, Epic Games (Epic Games, Inc., 1991) Unreal Engine 4 (2014) VR rendering platform along with Nvida's PhysX (Huang et al., 1993; Nvidia, 2017) physics engine were implemented primarily because of their ubiquity in academia as well as in the retail computer gaming industry (Batchelor, 2014; Bender et al., 2014).

In the final design iteration, the hardware architecture would have to be integrated in such a way that, given the input/output parameter specifications, researchers could implement a steering component module or other hardware without requiring expertise in the overall simulator programming details.

Simulator Design

The simulation environment employs a Logitech® G27 simulator-grade steering wheel, console, and pedals. The device provides force feedback, helical gearing, and 900° end-to-end steering. The stainless-steel and leather construction add to its realism. The console is mounted in a Playseat® frame/seating system. The driver seat, pedals, and steering console are fully adjustable within the frame, which accommodates a very wide range of test subjects. The visual system consisted of two display components having different functions. The first being a 2D LCD monitor for observation by the researcher, and the second being a 3D Oculus Rift Virtual Reality (VR) system for use by the driver test participants, which is a minimally obtrusive VR system.

The model upon which the testing scenario was designed was based on a 2005 Lotus Elise—in large part due to the Elise/Exige being the last sports cars sold in the U.S. with unassisted, single-ratio rack-and-pinion steering (Sherman, 2012). The Lotus Elise can maintain traction in a turn on a closed track while generating a lateral force of 1g (measured with a Motorola smartphone inertial measurement unit), so that limit was used to constrain the simulated vehicle action through a slalom course in the synthetic environment real-world slalom course analog.

The final parameters for designing the testing course were derived by iterating (using the simulator) through successive approximations of simulated vehicle velocity, inter-gate distance, and turn radius at the gate apex of the virtual track that would simulate the 1g target. Key to the design, a steady state in driver performance was observed to have been reached within a course of 20 slalom gates. Employing these parameters to mimic the experience of operating the modeled vehicle through a slalom track, the simulation would accelerate the simulated vehicle—based on it's mass of 750 Kg—to a velocity that could be easily reduced as each apex was reached so that the 1g limit would not be exceeded. The course and vehicle reaction were finally validated using the Lotus on the analogous closed-circuit track.

The track parameters are listed in Table 3.2 and the value for g-force were checked using the following calculation:

$$\frac{\frac{vr}{r}}{1g} = \frac{\frac{6r}{3.5}}{9.8} = \frac{10.29}{9.8} \approx 1g$$

Table 3.2: Virtual slalom track parameters

Track dimension	Value
Max vehicle velocity:	9m/s
Turn apex velocity	6m/s
Gate count:	20
Gate interval:	15.25m
Gate offset:	7m
Gate width:	3m
Track width:	10m
Track length:	640m
Distance to first gate:	135m
Distance after last gate:	200m
Turn radius:	3.5°

Figure 3.2 illustrates how the slalom gates were measured and placed into the track layout.

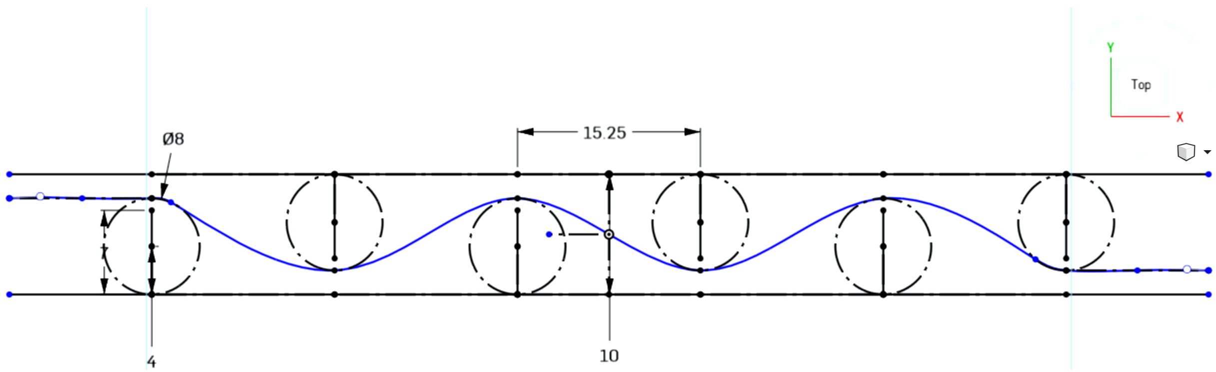

Figure 3.2: Path through a set of gates

Figure 3.3 more-precisely illustrates the dimensions used to achieve the desired g-forces. Vehicle velocity ranging from 6 m/s to 9 m/s (approx. 15-20 mph) constituted "moderate speeds" for the purpose of this simulation. The otherwise ambiguous term lacks a fixed metric definition and was not relayed to test participants.

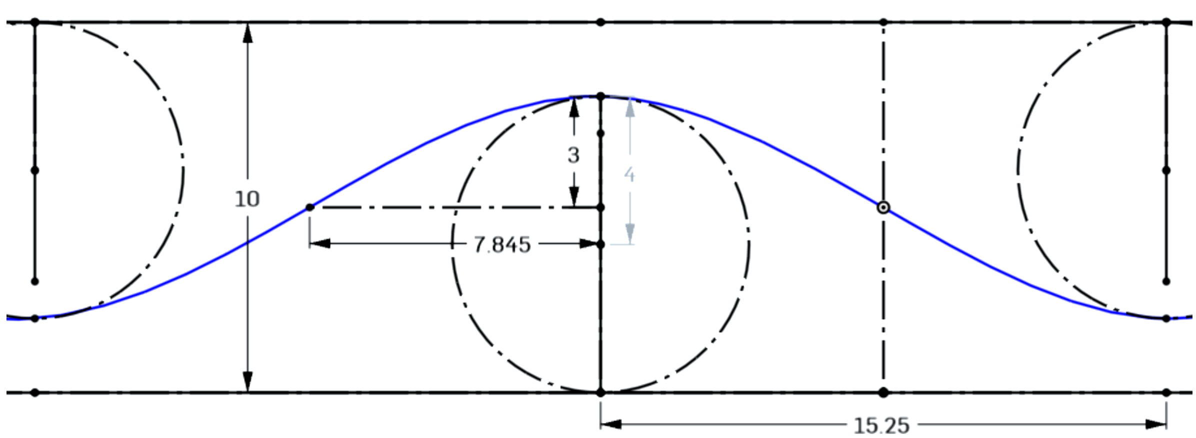

Figure 3.3: Path through a single gate

The key component of the multivariate-ratio steering system used in this study is the method by which the steering-wheel input is altered to constrain the steering-wheel range to 225°. The fundamental reduction of 900° to 225° produces a steering ratio that would render a vehicle uncontrollable at all but the lowest speeds. Where it would be most desirable to employ a greater ratio in parking situations, the driving experience at highway speeds should provide the same degree of control as conventional steering (i.e. no discernible steering action relative to conventional 900° steering). The multiple factors that would vary the ratio consist of the following:

- Vehicle velocity (slower = more effect; faster = less/none)
- Turn radius (small radius = more effect; larger = less/none)
- Wheel-turn acceleration (increases effect proportionally)

The term “effect” above is inversely proportional to the magnitude of the input (steering) signal remapping. That is to say, no remapping of the signal equates to an unmodified input signal; this would map to a linear 4:1 (900°:225°) steering-increase factor compared with conventional steering. The greater the magnitude of signal modification results in a reduction of that ratio—ultimately matching 1:1 (that of conventional steering). Note, however, from the chart; if the algorithm is applied much beyond 70 miles/hour, the steering curve drafts beyond horizontal, and would result in steering in the opposite direction of the wheel turn. The programming limits the application of the algorithm before that point is reached. The graph in Figure 3.4 on page 47 illustrates how the steering input signal would be remapped at selected speeds.

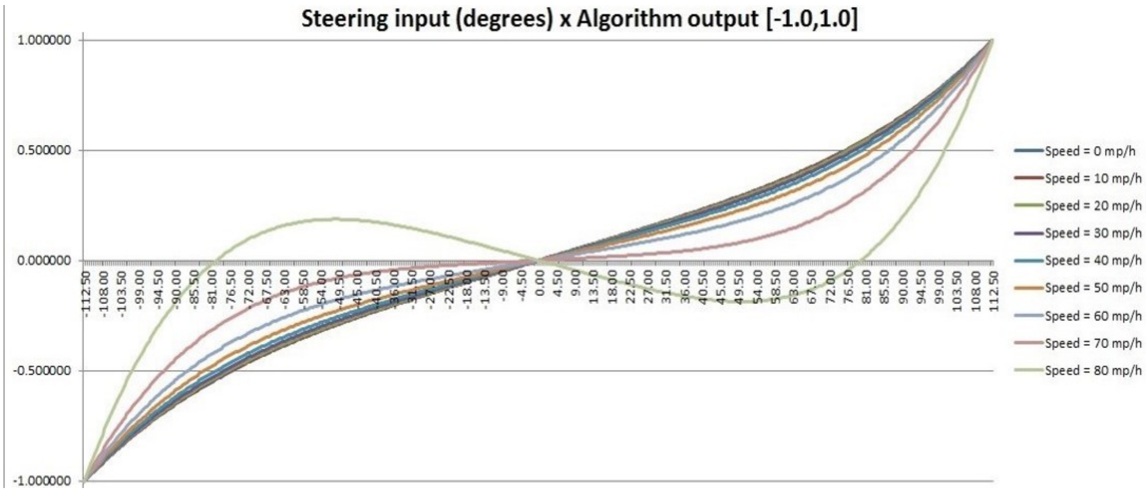

Figure 3.4: Reduction mapping applied to steering input

The following formula it the foundation of the steering algorithm employed by the simulator to remap the steering input:

$\theta = |\vartheta|\left(\frac{Cs+Cv}{\rho+Cv}\right)$, where:

θ = effective steering-wheel rotational angle

ϑ = actual steering-wheel rotational angle

ρ = ratio of conventional to actual steering-wheel rotational travel [4]

Cs = steering coefficient = $1 + s \times m \times |\vartheta|^{d_g}$

Cv = velocity coefficient = $(\rho - V^{d_v})/1054$

d_g = gain exponent [3]

d_v = velocity exponent [2]

m = d_g/ρ

s = sign = $\begin{cases} -1 \text{ if } \theta < 0 \\ +1 \text{ otherwise} \end{cases}$

The effective rotational steering angle (θ) is further augmented in proportion to the acceleration rate effected upon steering-wheel rotational rate. The following formula is used to modify the base θ:

$$\theta = \theta \times \Delta\theta / \Delta T, \quad \text{where:}$$

$\Delta\theta$ = periodic angular rotation in degrees

ΔT = duration of period in microseconds

The following code segments were used in the experimental simulator to implement the Multivariate Steering System:

```
static double theta0        = 0;
static double thetaRef      = 450;                  //  1/2 of 900 deg
static double thetaMax      = 112.5;                //  1/2 of 225 deg
static double ratioTheta    = thetaRef / thetaMax;  //  4
static double lowerCutOff   = 0;
static double upperCutOff   = 65;
static double gainExp       = 3;
static double velocityExp   = 2;
static double slope         = gainExp  / ratioTheta;  // .75
static unsigned long long   time0 = 0;


STEERINGSIMULATORLIB_API void SetUpperCutOff( int speed )
{
    upperCutOff = speed;
}


STEERINGSIMULATORLIB_API void SetLowerCutOff( int speed )
{
    lowerCutOff = speed;
}
```

```
STEERINGSIMULATORLIB_API double Scale( double             thetaInput,
                                      double             velocity,
                                      unsigned long long uSecNow )
{
    double signTheta         = abs(thetaInput) / thetaInput;
    double thetaOutput       = thetaInput;
    double coeffSteering     = 0;
    double coeffVelocity     = 0;
    double gain              = 0;
    double normalizer        = 0;
    double scaler            = 1;

    velocity = ( velocity < lowerCutOff ) ? lowerCutOff : velocity;
    velocity = ( velocity > upperCutOff ) ? upperCutOff : velocity;

    coeffSteering    = 1 + (pow( thetaInput, gainExp )
                         * ratioTheta * signTheta * slope);
    coeffVelocity    = ratioTheta - (pow( velocity, velocityExp ) / 1054);
    gain             = (coeffSteering + coeffVelocity);
    normalizer       = (ratioTheta    + coeffVelocity);
    thetaOutput      = thetaInput * gain / normalizer;

    if ( uSecNow != 0 )
    {
        scaler = Augment( thetaInput, uSecNow );
        scaler = ( scaler > 1 ) ? scaler : 1;
    }
    else scaler = 1;

    return ( scaler * (abs( thetaOutput ) > 1 ) ? signTheta : thetaOutput);
}


STEERINGSIMULATORLIB_API double Augment( double             thetaInput,
                                        unsigned long long uSecNow )
{
    unsigned long long  time1            = 0;
    unsigned long long  deltaTime        = 0;
    unsigned long long  divisor          = 1000;     // usec to msec conversion

    time1            = uSecNow / divisor;              // now working with msec
    deltaTime        = ( (time1 - time0) > 0 )    ? (time1 - time0) : 1;
```

```
deltaTime        = ( deltaTime > 100000000 ) ? 100000000 : deltaTime;
theta1           = thetaInput;
deltaTheta       = (theta1 - theta0);
steeringRate     = deltaTheta / deltaTime;

theta0 = theta1;
time0  = time1;

return abs( steeringRate );
```

Questionnaires

Eligibility Questionnaire: The Eligibility questionnaire (previously described) was completed by each participant prior to the experiment. The questionnaire is included in its entirety in the Appendix.

Demographic Questionnaire: A Demographic questionnaire was completed by each participant prior to the experiment and included the age and gender information referenced in hypotheses 2 and 3. Additionally, the questionnaire asks several questions about a participant's education level, degree of computer/game-console usage, and experience as a motor vehicle operator or passenger. The questionnaire is included in its entirety in the Appendix.

Usability Questionnaire: A Usability questionnaire (Rivera et al., 2010) was completed by each participant following each of the two simulation vignettes. The questionnaire consists of 50 statements, which are grouped within eight categorizes: (a) Simplicity, (b) Usefulness, (c) Functionality, (d) Consistency, (e) Proficiency, (f) Satisfaction, (g) Behavior, and (h) Need for improvement. Participants indicated their agreement to each of the statements by marking a Likert-rating scale response line. The response line contained the following five choices: 1 = Completely Disagree; 2 = Disagree; 3 = Somewhat; 4 = Agree; 5 = Completely Agree. Statements that scored negative responses higher were reverse-remapped using the SPSS statistical package, and all of the questions were consolidated into their respective categories. The questionnaire is included in its entirety in the Appendix.

Subjective Questionnaire: A Subjective-response questionnaire was completed by each participant at the end of the experiment so that a participant could express input not otherwise solicited about the experiment. The questionnaire is included in its entirety in the Appendix.

Experimental Procedure

Sequence

1. **Informed Consent and Questionnaires:** Upon arrival at the research laboratory, the experimenter verified that the participant was scheduled for the experiment. The experimenter then escorted the individual to the designated lab space. Once the participant was seated, the experimenter administered the consent form before proceeding to the next step. After acknowledgement of the informed consent, the experimenter asked a series of pre-experimental questions to verify inclusion/exclusion criteria. Per the questionnaire, individuals who did not possess a current Driver License, did not have normal or corrected-to-normal vision, or answered that they had experienced a seizure or had a prior history of seizures were excused from the study. Verbal responses from the participant were documented in writing by the experimenter. This initial process lasted approximately ten minutes. Next, the Demographics Questionnaire was administered followed by participant briefings.

2. **Simulator Briefing:** The user interface training was a short orientation of the driving simulator lasting approximately five minutes. The following points were communicated to the participant:

    - The driving simulator would use a three-dimensional, stereoscopic Virtual Reality (VR) device rather than a two-dimensional display monitor (or monitors).
    - The driver's only input would be vehicle direction using a steering wheel. Simulated vehicle speed would be controlled by the simulation scenario.
    - The simulator would have two interchangeable steering profiles that could feel and respond differently with respect to the driver's perception. The participant would execute the scenario twice and would experience both steering profiles in random order (a measure to mitigate learning effect—but was not explained to the participant).

3. **Task Briefing:** The task vignette was described to each participant, and that he/she would perform it twice—and would experience both steering profiles in randomized order. The task briefing would last approximately five minutes. The following objective was communicated to the participant:

   You are (The driver is) to negotiate a series of gates making up a slalom course on a closed (virtual) track. The objective is to complete the course without colliding with the stanchion cones that mark the gates, or with colliding with as few as possible.

4. **Simulation Vignette (1):** The participant would be helped into the simulator, fitted with the VR device, and the vignette staged in the simulation. When the participant was ready, the researcher would begin the simulation, which was be scored according to the number of gate collision occurrences. The initial steering system profile assigned to each participant was random. Upon completion, the VR device would be removed, and the participant helped out of the simulator. The combination of the vignette and simulator entry/exit would last approximately five minutes.

5. **Usability Questionnaire (1):** The participant would complete an initial usability questionnaire. The interval allowed for completing the questionnaire would be five minutes.

6. **Simulation Vignette (2):** The participant would repeat the simulation with the alternate steering profile. If profile A was assigned in the first vignette, the simulator would then be configured with profile B for the second, and vice-versa ("A" and "B" are arbitrary terms.) The repeated vignette would also last approximately five minutes.

7. **Usability Questionnaire (2):** The participant would complete a second usability questionnaire pertaining to his/her experiences with the second vignette. The interval allowed for completing the questionnaire would be five minutes.

8. **Subjective Response Questionnaire:** The participant would have an opportunity to provide his/her subjective experience with either or both of the simulations or steering systems using a free-format questionnaire. The interval allowed for completing the questionnaire was five minutes.

9. **Dismissal:** Upon completion of the experiment, the participant was be given a copy of the informed consent for his or her records. Participants who signed up to receive class credit were be awarded the credit on the IST Sona or UCF Psychology Sona systems. Finally, any participant who experienced fatigue or simulator sickness was dismissed upon verbal confirmation that the symptoms had subsided. Under normal circumstances, the participant would be dismissed after receiving the informed consent (course credit participants) or after receiving the informed consent and having received monetary compensation. This process would last approximately five minutes.

Measures

A crossover-type, repeated measures longitudinal study design was used to analyze the data. Each of the 27 female participants and each of the 27 male participants were evenly and randomly assigned to one of two study groups: the first, participants initially drove the Conventional Steering simulation, then followed with the Multivariate (experimental) System; the second, participants initially drove the Multivariate System, then followed with the Conventional System. The Conventional Steering scenario served as the control for comparison.

Evaluation of Performance

Each participant drove the scenario twice—once using the control steering system and once using the experimental steering system. Half drove the the former first, and the other half drove the latter first; assignment to each of the two groups was random. The participant was briefed on the simulator operation and instructed to drive through the slalom, clearing each of 20 gates and avoiding the stanchions. The simulator scored each cleared gate with one point—a total of 20 possible points—and recorded the scores in file directory folders named according to participant ID for comparative analysis.

Independent/Dependent Variables

The independent variable for both groups were the same:

- **Conventional (900°) Steering score:** a score from 0 to 20 indicating the number of gates negotiated without collision.
- **Multivariate ratio (225°) Steering score:** a score from 0 to 20 indicating the number of gates negotiated without collision.

The dependent variable in the analysis is Driver Performance.

Covariates

In addition to participant age and gender, there were several potential covariates recorded for further study, if needed.

Subjective Assessment of Performance

Selected responses to the Usability Questionnaire were used to assess each participant's evaluation of the Multivariate Steering System.

CHAPTER 4: FINDINGS

Introduction

This chapter presents the performance results based on participant scores recorded during the experiment, combined with data from the associated questionnaires. Descriptive statistics are presented, followed by an analysis of the relevant variables. The empirical data collected during the experiments, as well as the statistical methods used to analyze the results, are used to test each of the hypotheses upon which the experiment was based. IBM® SPSS® Statistics version 24 software was used for the analysis. Unless otherwise noted, the criterion used to reject the null hypotheses was evaluated at less than 0.05 ($\alpha < 0.05$).

Descriptive Statistics

This section of the chapter sets out the descriptive statistics. As noted in the preceding chapter, the research population is comprised 54 research participants. Additionally an electronic method of data collection was used to record participant scores during the experiment in order to ensure the integrity and completion of the data collection. Participant selection was purposive to the degree of providing near, or exactly even numbers of males and females, but otherwise non-purposive with regard to selection and scheduling.

Gender

The final population that was tested consisted of 27 females and 27 males. This balance was desired in order to examine gender comparisons with respect to human performance within the context of the simulation experiment. This distribution is listed in Table 4.1 on page 57.

Table 4.1: Sample population gender distribution

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Female	27	50.0	50.0	50.0
	Male	27	50.0	50.0	100.0
	Total	54	100.0	100.0	

Age

The sample population was selected primarily from a university environment. This accounted for the higher percentage of participants clustered in the early-twenties range. Figure 4.1 shows the distribution by percentage.

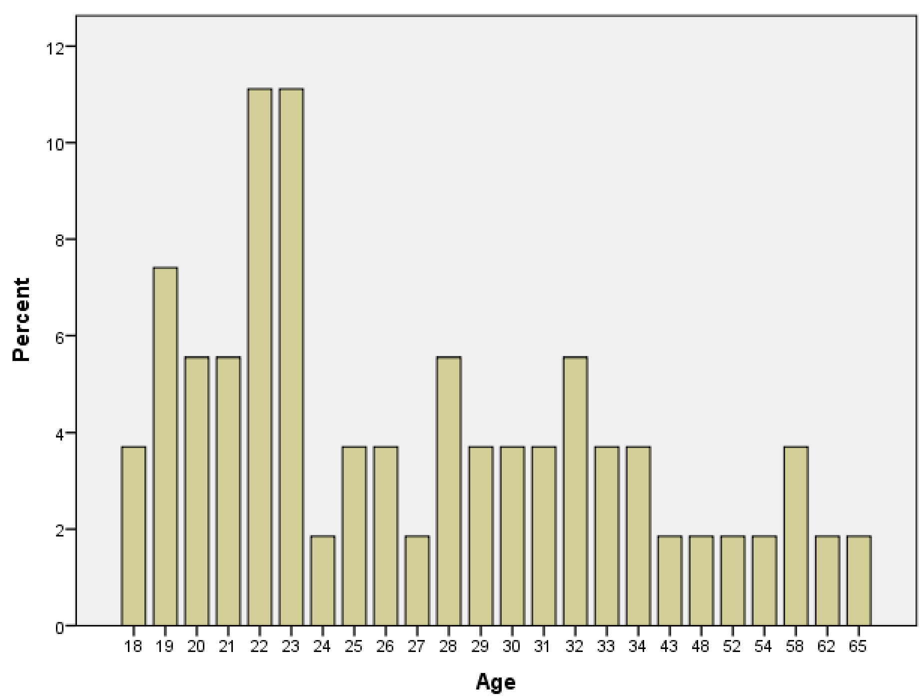

Figure 4.1: Distribution of participant ages as percentages

A different perspective of the age distribution shown in Table 4.2 tells us that 85% of the participants were under 35 years of age during the study.

Table 4.2: Sample population generational distribution

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Under 35	46	85.2	85.2	85.2
	35 or older	8	14.8	14.8	100.0
	Total	54	100.0	100.0	

Race

The sample population's race (or cultural self-identification) distribution is illustrated by percentage in Figure 4.2 and further broken down by count in Table 4.3.

Table 4.3: Sample population race distribution

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Middle-Eastern	1	1.9	1.9	1.9
	Caucasian	27	50.0	50.0	51.9
	Asian	7	13.0	13.0	64.8
	Hispanic	12	22.2	22.2	87.0
	Black	5	9.3	9.3	96.3
	Multi-Racial	2	3.7	3.7	100.0
	Total	54	100.0	100.0	

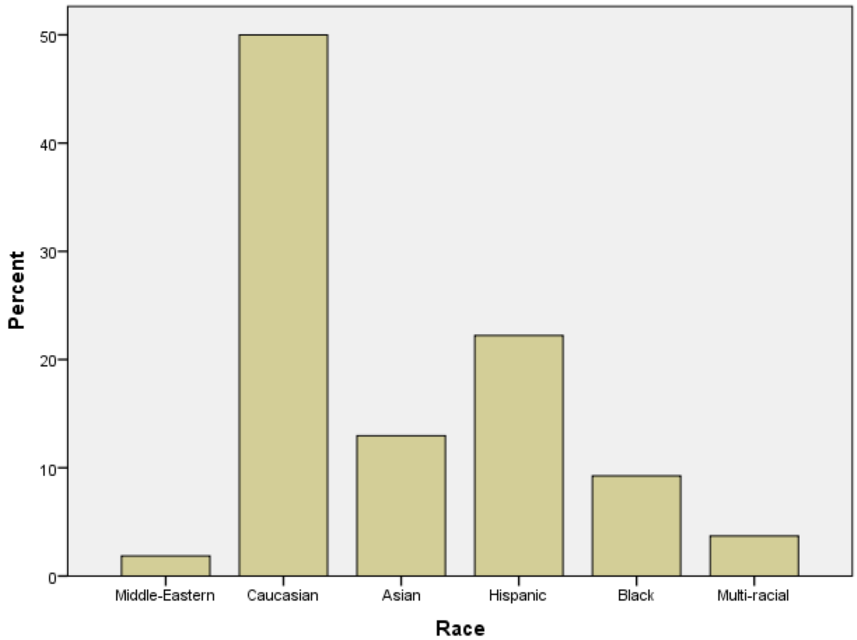

Figure 4.2: Distribution of participant race as percentages

Number of Years Driving

Participant driving experience (by count of years driving) was grouped into the following categories: (i) less than three years; (ii) three to five years; (iii) five to 10 years; (iv) 10 to 15 years; (v) more than 15 years. Figure 4.3 on page 60 illustrates the distribution by percentages.

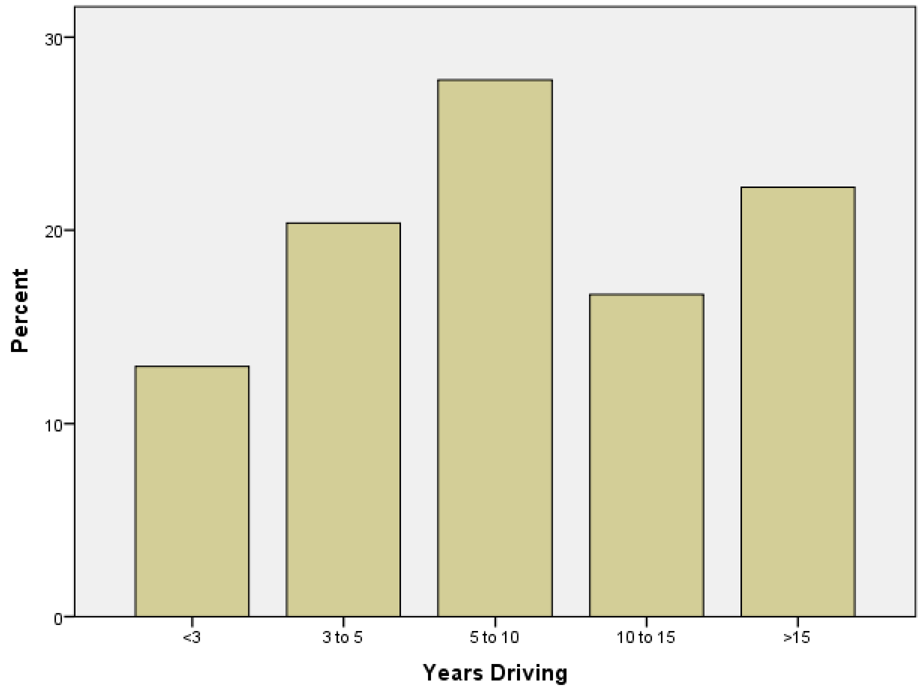

Figure 4.3: Distribution of participant driving experience

Computer Proficiency

Participants were also asked for a self-assessment of their computer proficiency. Their scores were grouped according to the following Likert-scale categories: (i) poor; (ii) below average; (iii) average; (iv) above average; (v) proficient. Figure 4.4 illustrates the distribution by percentages. 87% of the participants assessed their computer proficiency as above average or better.

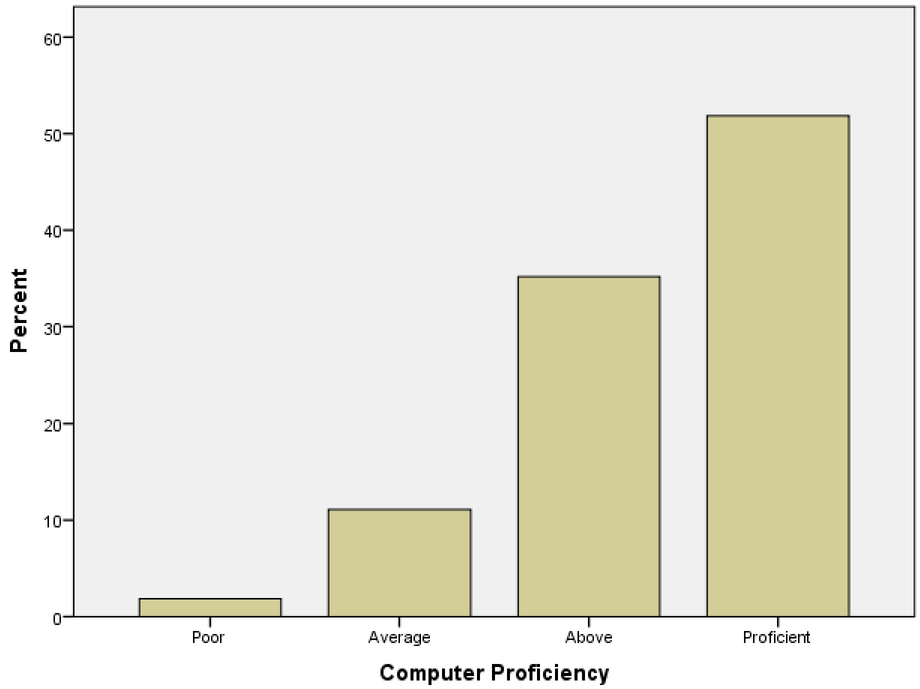

Figure 4.4: Distribution of participant computer proficiency

Statistical Analysis

Ceiling Effect

In the experiment, human performance scores were derived from the count of gates the participant (driver) successfully traversed in a 20-gate slalom course. If collisions with one or more stanchion occurred, the gate to which that stanchion belonged was not included in the tally. However, expertise beyond a score of 20 was not measured. It follows that, given the sufficiently-high skill level of the population, there would be a ceiling effect at 20 with a left-skew toward the lower scores. As a result, the collective set of scores is not parametric. To account for this, some statistics were calculated using a reflected-inverse version of the score, and in other cases, non-parametric statistical tests using unmodified scores were employed.

Residual Learning Effect

In order to rule out (or confirm) any significant residual learning effect resulting from successively operating the simulator to individually score participant performance using two steering systems, the experiment was carried out in a crossover-study fashion. That is, half of the male participants and half of the female participants were assigned randomly to undergo the simulation in sequence: Conventional steering-system first; Multivariate steering-system second (Conv-Multiv), while the other half were assigned the opposite sequence: (Multiv-Conv).

In order to identify any residual learning effect, the mean scores from participants driving the course while using the Conventional steering-system were calculated as two groups, Conv-Multiv and Multiv-Conv, indicating whether they drove the Conventional steering-system first or second, respectively. The grouped scores were compared in a series of two Independent Samples T-Tests having a null hypothesis that the distribution of scores would be the same across both orders of execution for each of the two sequence groups.

The comparison shows no significant difference in Conventional steering-system scores between the Conv-Multiv group (M = 17.87, SD = 3.9) and the Multiv-Conv group (M = 17.08, SD = 4.57; t (52) = .68, p = .5, two-tailed). The magnitude of the differences in the means (mean difference = .79, 95% CI: -1.53 to 3.1) was very small (eta squared = .009).

Similarly, the mean scores from participants driving the course while using the Multivariate steering-system also were calculated as two groups, Conv-Multiv and Multiv-Conv, and tested for the same null hypothesis.

The comparison shows no significant difference in the Multivariate steering-system scores between the Conv-Multiv group (M = 19.37, SD = 1.52) and the Multiv-Conv group (M = 19.13, SD = 1.62; t (52) = .56, p = .58, two-tailed). The magnitude of the differences in the means (mean difference = .24, 95% CI: -0.62 to 1.1) was very small (eta squared = .006).

To further substantiate these results in light of the non-parametric distribution of the data, Mann-Whitney U tests were also conducted on the same groupings.

When comparing the means of the Conventional steering-system scores, no significant difference was found between the Conv-Multiv group ($Md = 19$, $n = 30$) and the Multiv-Conv group ($Md = 19$, $n = 24$), $U = 297$, $z = 1.13$, $p = .26$, $r = .15$, interpreted as a small effect size.

Finally, when comparing the means of the Multivariate steering-system scores, no significant difference was found between the Conv-Multiv group ($Md = 20$, $n = 30$) and the Multiv-Conv group ($Md = 20$, $n = 24$), $U = 297$, $z = 1.13$, $p = .26$, $r = .08$, interpreted as small effect size.

Within the context of operating the simulator employed in this study a second time, these tests rule out to a statistical certainty any significant benefit to human performance because of residual effects gained from having operated the simulator previously.

Scoring: The Human Performance Results

Testing Hypothesis 1:

Drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.

Performance scores from the study were recorded and analyzed for the purpose of testing the first hypothesis and answering the first research question, "Will a multivariate steering-rate vehicle control system, which will allow a driver (i.e. study participant) to maintain uninterrupted hand positioning on a steering wheel during any steering maneuver measurably affect driver performance?".

An examination of performance scores collected from the simulation indicates non-parametric distribution of results. Reformulating the data by inverting and reflecting each score according to the formula: new datum = 1 / (K - original datum), where K = the largest possible value plus 1. yields results that are more parametric. A graphical illustration comparing non-converted scores (Figure 4.5) with the reflected-inverse manipulation of the scores (Figure 4.6) for the conventional steering-system scores can be seen on page 65. A similar comparison of non-converted and reflected-inverse manipulated Multivariate Steering-system scores can be seen in Figure 4.7 and Figure 4.8 on page 66.

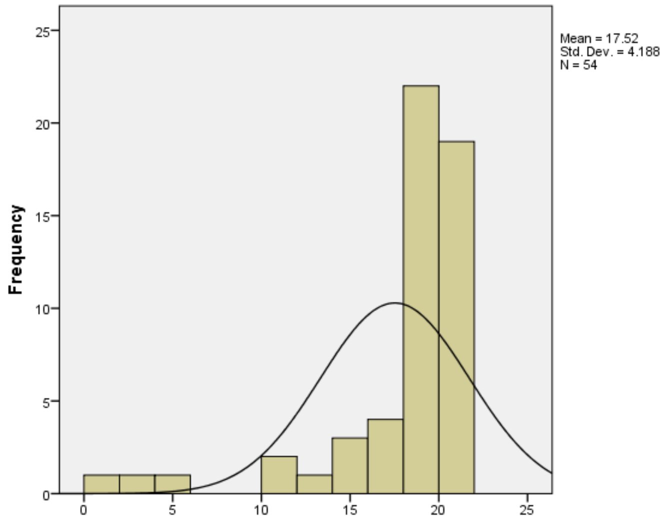

Figure 4.5: Performance scores using the conventional steering-system

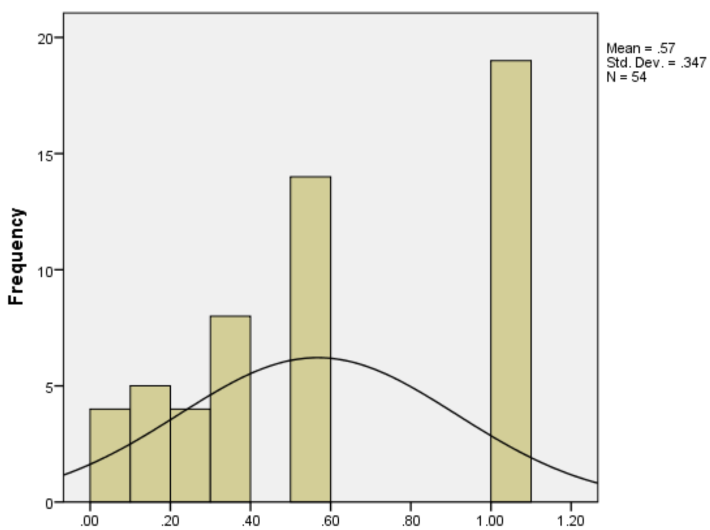

Figure 4.6: Reflected and inverse converted scores using the conventional steering-system

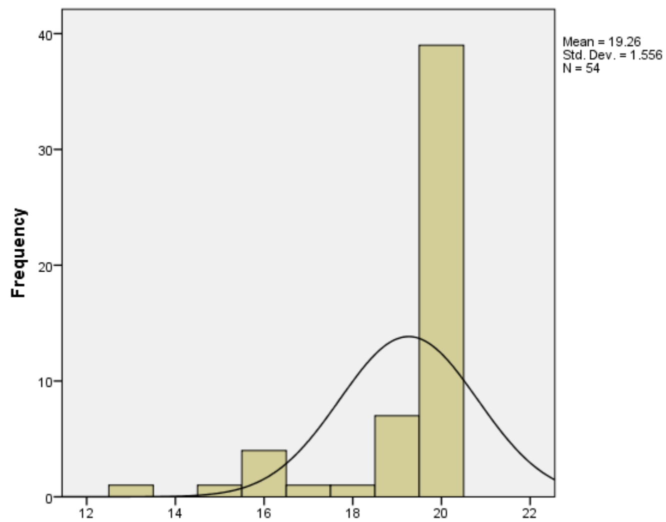

Figure 4.7: Performance scores using the Multivariate Steering-system

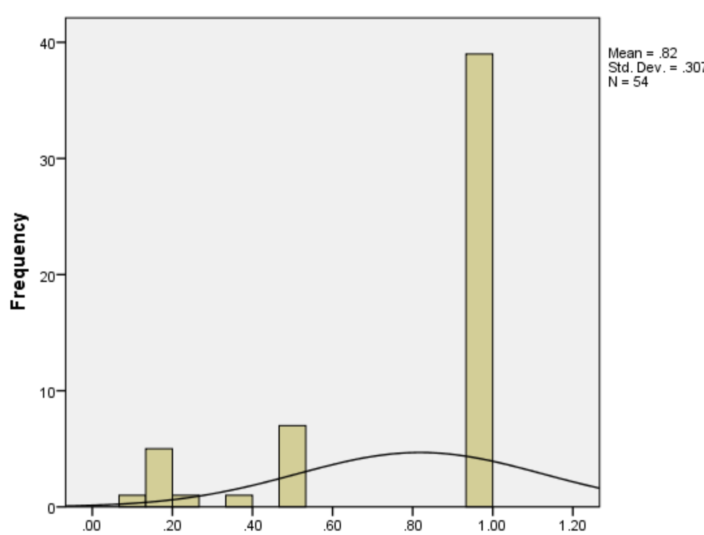

Figure 4.8: Reflected and inverse converted scores using the Multivariate Steering-system

Repeated Measures Testing

All of the participants "drove" the same simulated slalom track twice. The two simulated drives, however, were under different conditions. Specifically, each participant drove a simulated conventional steering-system, as well as a simulated multivariate steering-system. If the performance scores were normally distributed, the hypothesis would be tested using a repeated measures t-test. However, due to the non-parametric distribution of the data, it was necessary to utilize a corresponding alternative. The Wilcoxon Signed Rank Test was selected over using a repeated measures t-test with reflected and inverse converted scores. Preference was shown toward this method because the range of the reported means of the latter method (0.13 - 1.00) would not directly match the scale of the original data range (1 - 20), and therefore not be as easily associated with the scoring objective (20 gates) of the participants.

The null hypothesis to be tested specifies that there will be no significant difference between the means of performance scores measured while participants used conventional steering-system versus the scores measured while participants used the Multivariate Steering-system.

A Wilcoxon Signed Rank Test revealed a statistically significant improvement of performance scores measured while using the Multivariate Steering-system when compared to performance scores measured while using the conventional steering-system, $z = -3.5$, $p < .001$, with a medium effect size ($r = .34$). The median value derived from the Multivariate Steering-system scores ($Md = 20.6$) showed an increase over the median value derived from the conventional steering-system scores ($Md = 17.69$).

The results of the Wilcoxon Signed Rank Test are sufficient to reject the null hypothesis and conclude that drivers will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.

Subjective: Participant Preferences Findings

Testing Hypothesis 2:

Drivers in a simulated environment will prefer using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.

Participant preferences from the study were collected by means of written survey (reproduced in Appendix D) upon completion of the simulation analyzed for the purpose of testing the second hypothesis and answering an adjunct to the first research question, “Will drivers prefer operating vehicles equipped with Multivariate Steering-rate Vehicle Control, or will they prefer driving vehicles equipped with conventional 900° steering systems?”.

Upon completion of both vignettes, participants were asked for their subjective comparison of the two steering systems; they were asked to include which system they personally preferred, and/or would recommend to have implemented in vehicles in the future. 14.8% of participants (n = 8) either personally preferred the conventional steering system or recommended it for continued implementation. 7.4% of participants (n = 4) both preferred the conventional steering system and recommended it for continued implementation. 72.2% of participants (n = 39) either personally preferred the multi-variate steering system or recommended it for future implementation. 53.7% of participants (n = 29) both preferred the multi-variate steering system and recommended it for future implementation. One participant had no preferences (n = 1, N = 54).

The categorical tallies are listed in Table 4.4 and Table 4.5, and further illustrated in Figure 4.9 and Figure 4.10 on the following pages.

Table 4.4: Study participant steering-system preferences

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Conventional	8	14.8	14.8	14.8
	Multivariate	44	81.5	81.5	96.3
	No Preference	2	3.7	3.7	100.0
	Total	54	100.0	100.0	

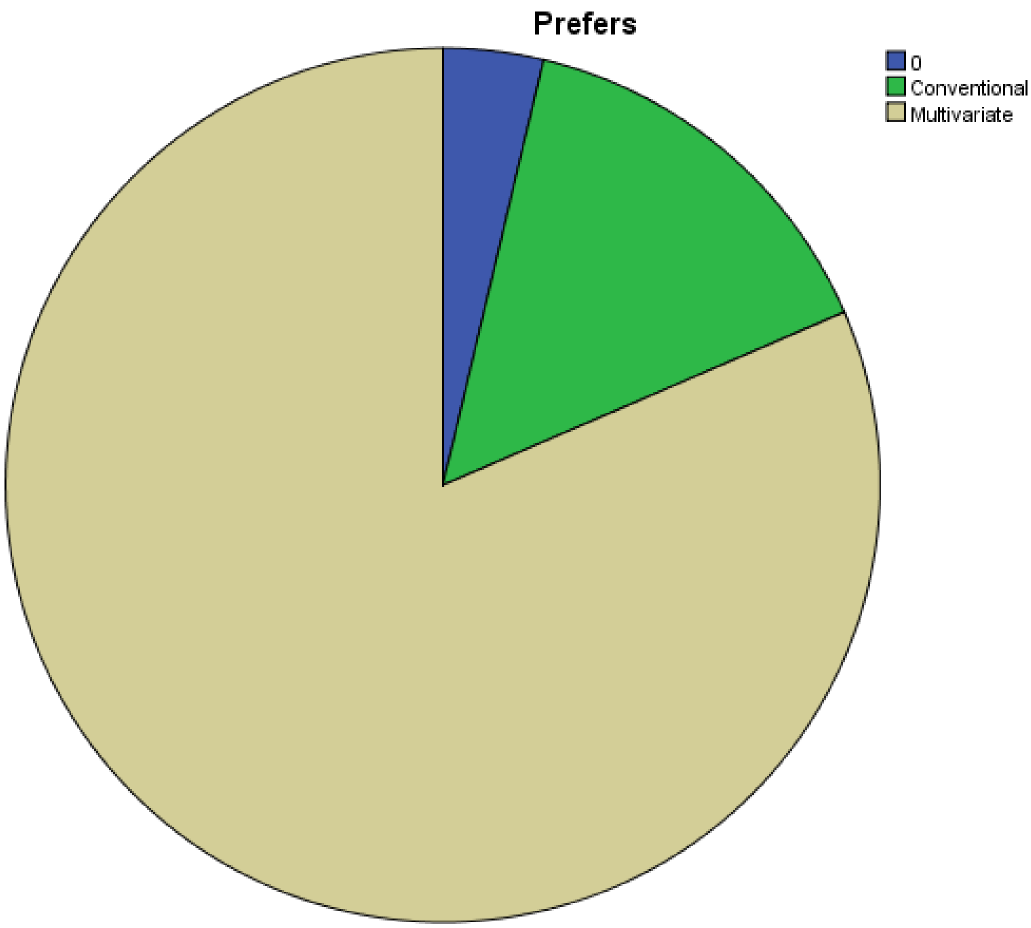

Figure 4.9: Preference

Table 4.5: Study participant steering-system would-recommend

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Conventional	4	7.4	7.4	7.4
	Multivariate	33	61.1	61.1	68.5
	No Preference	17	31.5	31.5	100.0
	Total	54	100.0	100.0	

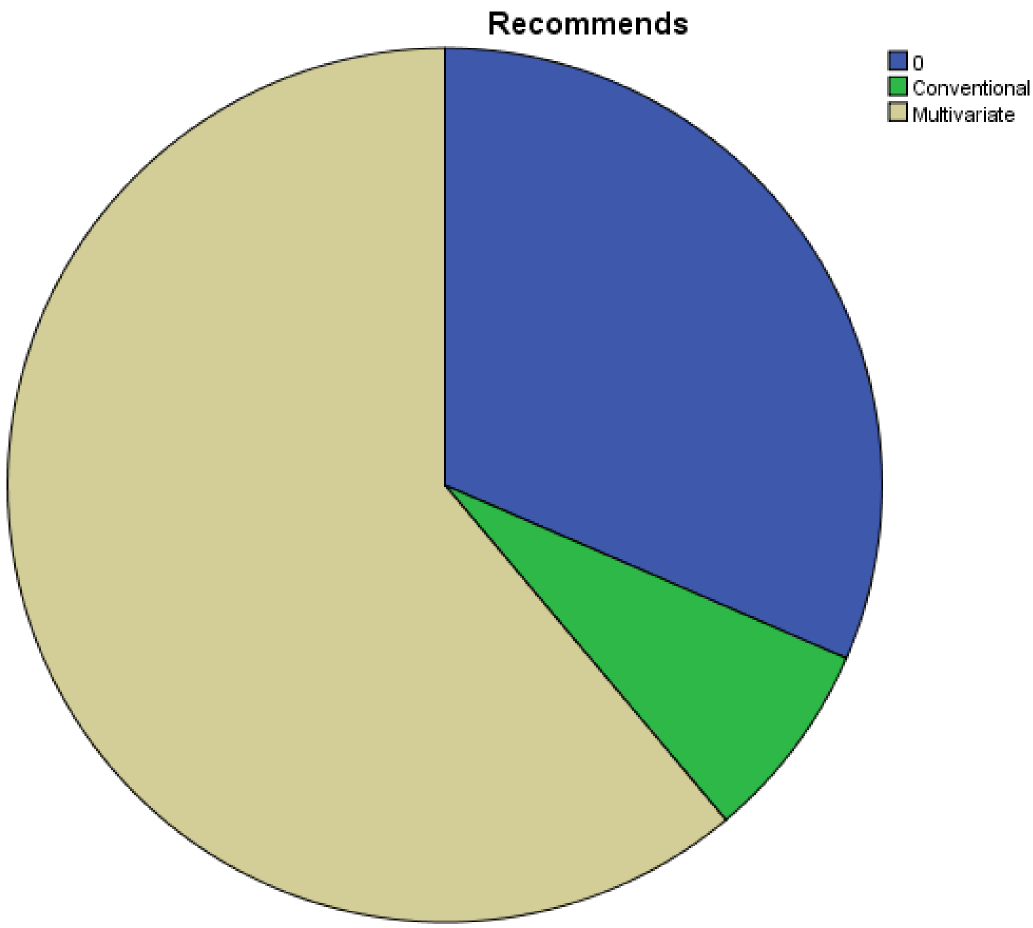

Figure 4.10: Recommendation

Questionnaire Results

A within-subjects analysis of variance was conducted to assess driver preference with respect to the type of steering system employed in driving simulations measured after each of two conditions (Conventional; Multivariate). There was a substantial main effect for condition, Wilks' Lambda = .34, F (8,46) = 11.43, $p < .001$, partial eta squared = .67, showing a preference for the Multivariate steering system.

Table 4.6 below (Likert scoring, 1 - 5), shows additional detail among the eight categorical groupings of questions presented in the survey document. Usefulness, Functionality, Satisfaction, Behavior, and Acceptability groupings showed greater difference in means than did Simplicity, Consistency, and Proficiency, although all eight groups indicated a preference for Multivariate Steering, further supporting the second hypothesis.

Table 4.6: Driver preference with respect to steering system type, by category

	Conventional Steering			Multivariate Steering			Pairwise Comparisons	
	n	M	SD	n	M	SD	Mean Difference	Std. Error
Simplicity	54	3.61	.79	54	4.25	.52	-.644	.125
Usefulness	54	3.13	.91	54	4.33	.53	-1.200	.142
Functionality	54	3.26	.99	54	4.28	.99	-1.023	.156
Consistency	54	3.50	.77	54	4.11	.57	-.607	.125
Proficiency	54	3.91	.77	54	4.46	.49	-.549	.110
Satisfaction	54	3.16	.99	54	4.13	.72	-.970	.165
Behavior	54	2.96	.71	54	3.91	.67	-.947	.132
Acceptability	54	3.05	.79	54	3.84	.62	-.891	.145

Assessment: The Effect of Gender

Testing Hypothesis 3:

Male drivers in a simulated environment will perform no differently from female drivers at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control.

Performance scores from the study were recorded and analyzed for the purpose of testing the third hypothesis and answering the associated research question, “Will gender correlate with performance differences?”.

In the prior section on page 64 evaluating the first hypothesis, the non-parametric nature of the performance scores was addressed, explaining why a more-parametric representation of the data (inverted-reflected scores) would be used to compare means. The same manipulation provides a more-normally distributed dependent variable in testing the third hypothesis employing an independent-samples t-test as well.

A Mann-Whitney U Test revealed no significant difference in performance scores between females (Md = 19, n = 54) driving a conventional steering-system in simulation and males (Md = 19, n = 54), U = 327.5, z = -0.67, p = .51, r = .09 driving the same simulation. Additionally, no significant difference was revealed between the same male drivers (Md = 20, n = 54) and female drivers (Md = 20, n = 54), U = 322.5, z = -0.9, p = .36, r = .09 when driving a multivariate steering-system in simulation.

The Mann-Whitney U Test results were not sufficient to reject the null hypothesis, which in this case, was the same as the hypothesis being tested. Therefore, from the results of this study, it cannot be concluded whether or not gender would be a factor explaining any hypothesized differences between the performance of men or the performance of women when driving either a conventional or multivariate steering system.

Assessment: The Effect of Age

Testing Hypothesis 4:

Younger drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control than older drivers.

Performance scores from the study were recorded and analyzed for the purpose of testing the third hypothesis and answering the associated research question, "Will age—(game-pad generation versus slide-rule generation)—correlate with performance differences?".

The fourth hypothesis was tested independently for each of the two simulated steering systems.

The first independent-samples t-test was conducted to compare performance scores for younger drivers (aged 18 to 40 years) and older drivers (aged 41 to 65 years) while driving a conventional steering-system in simulation. There was no significant difference in performance scores for younger drivers ($M = 18.3$, $SD = 2.57$) and older drivers ($M = 13$, $SD = 7.93$; $t\,(7.26) = 1.88$, $p = .1$). The magnitude of the differences in the means (mean difference = 5.3, 95% *CI*: -1.34 to 11.95) was moderately large (eta squared = .11).

The second independent-samples t-test was conducted to compare performance scores for younger drivers (aged 18 to 40 years) and older drivers (aged 41 to 65 years) while driving a multivariate steering-system in simulation. There was no significant difference in performance scores for younger drivers ($M = 19.48$, $SD = 1.19$) and older drivers ($M = 18$, $SD = 2.67$; $t\,(7.49) = 1.54$, $p = .17$). The magnitude of the differences in the means (mean difference = , 95% *CI*: -.76 to 3.72) was moderate (eta squared = .06).

Even though the high p values for each of the two tests indicate a low probability of significance concerning the difference in means, the actual mean-difference value of 5.3 (29%) when considered with the possibility of the non-linear performance score distribution, which may affect the effectiveness of the t-test, there is a compelling case for further evaluation employing an equivalent non-parametric test.

A Mann-Whitney U Test also revealed no significant difference in performance scores while driving a conventional steering-system in simulation between younger drivers (Md = 19, n = 46) and older drivers (Md = 15, n = 8), U = 139.5, z = -1.12, p = .26, r = .15.

Collectively, the t-tests for independence, supported by the results of the Mann-Whitney U Test employed in reevaluating the non-parametric data, strongly suggest that the null hypothesis cannot be rejected. Therefore the fourth hypothesis is not supported, and the research question, "Will age—(game-pad generation versus slide-rule generation)—correlate with performance differences?" cannot be affirmed.

Summary: Study Results

Research Question 1: "Will a multivariate steering-rate vehicle control system, which will allow a driver (i.e. study participant) to maintain uninterrupted hand positioning on a steering-wheel during any steering maneuver, measurably affect driver performance in a simulated environment?"

Hypothesis 1: "Drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems." The null hypothesis stating that drivers would perform no differently between the two steering systems was rejected. The same statistical methods additionally resulted in a higher mean-performance score for the Multivariate Steering-rate Vehicle Control.

Hypothesis 2: "Drivers in a simulated environment will prefer using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems." The null hypothesis stating that drivers would have no preference between the two steering systems was rejected. The same statistical methods additionally resulted in a higher mean-preference for the Multivariate Steering-rate Vehicle Control.

Concurring results from collectively evaluating Hypothesis 1 and Hypothesis 2 affirm the first and second research questions, respectively.

Research Question 3: "Compared with study participants' respective performance driving a conventional steering system (in simulation) versus a multivariate steering-rate vehicle control system designed for the purposes of this research, will gender be a factor to a statistical significance?"

Hypothesis 3: "Male drivers in a simulated environment will perform no differently from female drivers at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control.", could not be rejected using the appropriate statistical methods. Therefore, the second research question cannot be affirmed.

Research Question 4: "Compared with participants' respective performance driving a conventional steering system (in simulation) versus a multivariate steering-rate vehicle control system designed for the purposes of this research, will age be a factor to a statistical significance?"

Hypothesis 4: "Younger drivers in a simulated environment will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control than older drivers.", could not be rejected using the appropriate statistical methods. Therefore, the third research question also cannot be affirmed.

CHAPTER 5: DISCUSSION

Summary

The main thesis motivating this research introduces the notion that—given emerging technologies inclusive of electronic steering systems—the conventional (linear) steering-response paradigm need not be presumed as the basis for new steering system technologies. The research herein investigates alternatively accommodating paradigms from a human-factors perspective, and developing a model within which to test human performance within a finite set of steering scenarios.

Rather than providing a conventional linear relationship between the steering-wheel and the road wheels of a vehicle, an experimental model was designed to actuate a steering response based upon a dynamic curve relationship. The response curve computes a normalized sigmoid curve with an amplitude variance dependant on vehicle speed and acceleration of steering-wheel rotation. The resulting curve serves as a translation function between steering input and steering output. In other words, the steering output signal is a product of plotting the steering input signal against the translation curve. Additionally, the variable-rate signal function in the experimental model resolves to a steering-wheel rotational travel of 225°—a 75% reduction from the conventional 900° systems. This allows complete wheel actuation without requiring the removal or repositioning of a driver's hands on the wheel.

Using this model, a novel simulator was used to test driver participants under two conditions (linear-response model and multivariate curved-response model) simulating the same ten-gate slalom course scenario. Statistical analysis of both the score results and the participant surveys indicate significantly better performance and greater preference, respectively, for the multivariate system. The impact from these findings derives from the structure of the comparative analysis itself, and potentially manifests as a standardized framework with which to test and evaluate new automotive steering systems in the near future.

Evaluation of Methods

The Simulator

Driving simulators are plentiful, can be highly configurable, and cover broad ranges of both application and fidelity. However, given the specific objectives of this study, it became necessary to design and implement a novel design incorporating unique steering configurations simulating an unconventional steering paradigm. Additionally, the simulator needed capability of measuring human performance when using disparate steering configurations simulating significantly-different steering paradigms.

The core steering algorithms and physics were designed and tested using the academically-recognized automotive and driving simulation software, TORCS, and its successor Speed Dreams. In order to facilitate high-fidelity 3D visuals and support commercial off-the-shelf (COTS) hardware, the simulation was migrated to a software platform based on Unreal Engine 4 and Nvida PhysX. The implementation combining the software platform with a hardware platform primarily consisting of an Oculus Rift stereoscopic VR head-mounted display (HMD)and Logitech G27 steering-wheel provided a framework for the prescribed simulations and produced measurable results for data analysis.

The collective simulation framework is a modular system that is configurable, flexible, and relatively inexpensive. It can be implemented in a variety of testing or experimental scenarios to address a broad range of research

The Questionnaire

The Mouloua Usability Questionnaire (Rivera et al., 2010) adds relevant categories such as Simplicity and Functionality to the categories, Usefulness, Satisfaction and Ease-of-use to the USE Usability Questionnaire (Lund, 2001) from which it was derived. The adaptation used in this study provides its most significant data within the categories of Usefulness, Functionality, Satisfaction, Behavior, and Acceptability. The data collected from the resulting survey provide clear preference overall for the augmented steering system over the paradigm of conventional steering, and accordingly complements the findings from the simulator experiments. Collectively, the scores from these dimensions of usability were used to conclude user preference toward the Multivariate Steering-rate Vehicle Control system.

Statistical Tests

The participants consisted of 54 licensed drivers, 27 of which were female and 27 of which were male. The minimum sample size (N = 23) was derived by bivariate normal model correlation using G*Power statistical software.

In order to test the first hypothesis, "Drivers will perform better at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.", the Wilcoxon Signed Rank Test was selected as the statistical test; results were sufficient to reject the null hypothesis. Normally, a repeated measures t-test would normally be indicated for within-subjects testing of a repeated scenario under different conditions. However, due to the non-parametric distribution of the test data, the corresponding alternative was selected.

In order to test the second hypothesis, "Drivers will prefer using vehicles equipped with Multivariate Steering-rate Vehicle Control, compared with vehicles equipped with conventional 900° steering systems.", a within-subjects analysis of variance was selected as the statistical test; results were sufficient to reject the null hypothesis.

In order to test the third hypothesis, "Male drivers will perform no differently from female drivers at moderate speeds using vehicles equipped with Multivariate Steering-rate Vehicle Control.", the Mann-Whitney U Test was selected as the statistical test; results were not sufficient to reject the null hypothesis. This alternative test was also selected due to non-parametric data.

Conclusions

Practical Implications

The ability to test driver performance in a repeatable and standardized way, means that the development and refinement of steering-oriented technology and products can be implemented in real-world settings with predictable results. The 225° Multivariate-rate Steering System developed as part of this research study serves as a good example. Reliable study data show that both male and female drivers will prefer and perform steering maneuvers (at least, ones resembling the turns traversed within this simulated slalom) better with this system than with conventional predecessors.

A performance measurement framework standardized across both Academia and Industry would be a benefit to both. Developers and designers will be able to use data from their own virtual-world testing to predict whether a new design or concept is on the right track with respect to design objectives and ultimately customer value before expending resources toward real-world testing. Properly structured, extensions and nuances to the framework could be implemented to support applications requiring more-specialized parameters, such as designing for drivers having special needs. For example, steering-system functional characteristics could be comparatively optimized to accommodate individuals afflicted with upper-body deficits or limited use of either or both arms. The human-factors approach distinguishing this research further distinguishes, by extension, associated steering products featuring purposeful improvements—contrasted with arbitrary improvements that might be brought about predominantly to showcase technological advancements.

Limitations

Given the practical constraints of this study, the selection of testing scenarios was limited. Ideally, a greater number of trials, as well as many other scenarios that may challenge a driver's steering competence would have (and ultimately, should be) tested. These would include, but are not limited to:

- Parallel parking
- Collision avoidance maneuvers
- Negotiating decreasing-radius turns
- Law enforcement methods such as Pursuit Intervention Technique (PIT)
- Reversing a vehicle
- Spin or drift recovery
- Real-world variables related to weather, terrain, obstacles, etc.

Additionally, diminished dexterity imposed through shuffle or hand-over-hand steering impacting vehicle control, and by extension, driving safety, is presumed in this study. Further investigation and testing is warranted before concluding that steering error mitigation through constant two-handed steering can be causally correlated to improved driving safety.

Recommendations

Even though physiological assessment during simulation was beyond the scope of this study, future developers may wish to evaluate physiological responses. A logical next step in the application of this methodology geared toward accommodating a physiometric dimension could implement a more-sophisticated full-motion simulator platform. Through its use, further experimentation, such as comparisons between 2D display monitors versus 3D HMDs (such as the Oculus Rift), could be conducted to establish or rule-out perception confounds in terms of experience and response timing—as well as monitoring other factors that may have a measurable effect on testing.

Ultimately, the development of a physical vehicle with the same modular configurability as its simulation counterpart is recommended. The collective testing & evaluation suite would ostensibly exist as an open-source standard for the benefit of both Academia and Industry.

Additional Study

Although outside the scope of this experimental design and therefore not formally evaluated using statistical methods, it seemed noticeable that—for female subjects who performed poorly in the first half of the simulated slalom course—driving performance tended to improve while negotiating the second half of the test track with respect to the first half, but only when using the augmented steering system. This was not the case when female subjects drove the same test track during the simulation employing conventional steering. There seemed to be no significant improvement under the same conditions for male subjects—at least, not to a noticeable degree.

The findings relating to the overall performance parity between female and male drivers are constrained by the statistical methods selected for this experimental design. More-subtle performance differences could be explored using additional, more-comprehensive statistical tests. The implication of this notion is that gender may play a role in adaptability to departure from conventional steering systems. Data from this study exist to the granularity of first-half versus second-half scores from the slalom course, as well as identification of individual gates with which each driver collided. Evaluation of these results could facilitate further study investigating the role of gender in adaptability to evolving steering systems in automobiles.

Future Directions

The absence of accessible, published methods and statistical results regarding automotive steering development and technology where driver performance is a concern, was an important observation illuminated during this study. An information-sharing substructure for disseminating new research and advancements between Industry and Academia clearly has not been forthcoming—either from Industry or Academia. The importance of such a bridge has positive implications in both engineering mechanical design as well as in human-factors concepts. This sort of collaboration in the advent of self-driving cars and related technologies likely to require electronicallyadapted steering systems, ensures standardized methods for measuring driver performance and adaptability. Information access and standardization will be necessary if we are to reevaluate the paradigms governing the designs of emerging systems.

Well suited toward novel system design, simulation is a valid, convenient, and expedient tool to use in the early stages of performance evaluation prior to committing the resources necessary to build physical prototypes for development and testing. A standardized driving-simulator platform that ostensibly supports features geared toward human-performance evaluation may be developed from the novel simulator design used in this study. The commercial, off-the shelf (COTS) and open-source components used in its hardware and software architecture already position it as part of a more-comprehensive simulation platform for Industry or academic efforts undertaking study and/or development of advanced steering systems.

Isolated-and-proprietary research and development in the automotive industry has been the status quo. Consequently, there exists a chasm between Academia, and industry engineers incentivized to focus on what is most marketable. Open-source projects/development have become part of the landscape of disruption to the status quo. A common simulation platform, bridging the automotive industry and Academia, has the potential to disrupt a decades-old trend and open the doors of cooperation. Open-sourced frameworks such as this one can put purposeful research in shared hands—inclusive of students limited by modest resources. Industry research and development aimed at best serving shareholders can be transformed into a broader category aimed at best serving the ultimate stakeholders: the public.

APPENDIX A: UCF IRB APPROVAL DOCUMENT

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Approval of Human Research

From: **UCF Institutional Review Board #1**
FWA00000351, IRB00001138

To: **Michael A. Xynidis** and Co-PI: **Petros Xanthopoulos**

Date: **October 04, 2016**

Dear Researcher:

On 10/04/2016 the IRB approved the following human participant research until 10/03/2017 inclusive:

Type of Review:	Submission Response for UCF Initial Review Submission Form Expedited Review
Project Title:	Assessing the Impact of Multi-variate Steering-rate Vehicle Control on Driver Performance in a simulation Framework
Investigator:	Michael A. Xynidis
IRB Number:	SBE-16-12493
Funding Agency:	
Grant Title:	
Research ID:	N/A

The scientific merit of the research was considered during the IRB review. The Continuing Review Application must be submitted 30days prior to the expiration date for studies that were previously expedited, and 60 days prior to the expiration date for research that was previously reviewed at a convened meeting. Do not make changes to the study (i.e., protocol, methodology, consent form, personnel, site, etc.) before obtaining IRB approval. A Modification Form **cannot** be used to extend the approval period of a study. All forms may be completed and submitted online at https://iris.research.ucf.edu .

If continuing review approval is not granted before the expiration date of 10/03/2017, approval of this research expires on that date. When you have completed your research, please submit a Study Closure request in iRIS so that IRB records will be accurate.

Use of the approved, stamped consent document(s) is required. The new form supersedes all previous versions, which are now invalid for further use. Only approved investigators (or other approved key study personnel) may solicit consent for research participation. Participants or their representatives must receive a copy of the consent form(s).

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

In the conduct of this research, you are responsible to follow the requirements of the Investigator Manual.

On behalf of Sophia Dziegielewski, Ph.D., L.C.S.W., UCF IRB Chair, this letter is signed by:

Signature applied by Patria Davis on 10/04/2016 10:04:36 AM EDT

IRB Coordinator

APPENDIX B: UCF PARTICPANT CONSENT FORM

Assessing the Impact of Multi-variate Steering-rate Vehicle Control on Driver Performance in a Simulation Framework

Informed Consent

Principal Investigator:	Michael Xynidis
Co-Investigator:	Petros Xanthopoulos
Investigational Site:	Institute for Simulation & Training University of Central Florida 3100 Technology Parkway, Orlando, FL 32826

Introduction: Researchers at the University of Central Florida (UCF) study many topics. To do this we need the help of people who agree to take part in research studies. You are being invited to take part in a research study that will include up to 50 people at UCF. You must be a licensed driver and have normal or corrected to normal vision to be included in the research study. Your participation is voluntary and you may withdraw at any time. The person doing this research is Michael Xynidis, MS from the Institute for Simulation & Training at UCF. Because the researcher is a doctoral graduate student, he is being guided by Petros Xanthopoulos, Ph.D., a UCF faculty advisor in the Industrial Engineering & Management Systems department.

What you should know about a research study:

- Someone will explain this research study to you.
- A research study is something for which you volunteer.
- Whether or not you take part is up to you.
- You should take part in this study only because you want to.
- You can choose not to take part in the research study.
- You can agree to take part now, and then later change your mind.
- Whatever you decide it will not be held against you.
- Feel free to ask all the questions you want before you decide.

Purpose of the research study: The purpose of this research initiative is to investigate the effectiveness in driver performance with steering systems that vary the amount of steering effect throughout the steering-wheel range, as well as according to vehicle speed. This type of steering system is called "proportional-rate steering". In these experiments, the simulated scenarios generated are used to assess driving performance under conditions that normally require repeated turns of a steering wheel. The specific objective of this experiment is to compare driving performance between two steering systems within a virtual environment—one conventional, and the other a variable proportional-rate steering system.

What you will be asked to do in the study: Before participation in the study begins, you will be asked a short series of questions to rule out conditions that would disqualify you from participation. In particular, you must be a currently licensed driver, and have had no history of seizures. Individuals who have a prior history of seizures cannot take part in this study.

This study uses a driving simulator incorporating a virtual reality (VR) vision device that is worn like a diver's mask. You will be instructed in the use of the simulator. You will then be briefed on the simulation task, which will be to negotiate your car through a series of traffic cones, colliding with as few as possible. By driving the simulation twice, you will operate up to two steering systems in random order. You will view the simulated driving environment only through the VR headset. During the course of driving the simulations, you will be asked to complete up to four surveys and questionnaires throughout the experiment, including a demographic survey, usability questionnaires, and a subjective comments form.

Location: This study is being conducted in buildings Progress II and Progress III at the Institute for Simulation & Training: 3100 Technology Parkway Orlando, FL 32826.

Time required: The expected duration of this study will not exceed 1 hour.

Risks: There are no foreseeable risks or discomforts other than those normally encountered in the daily lives of healthy persons. There is minimal risk that you may develop what is referred to as simulator sickness. It periodically occurs after exposure to prolonged, continuous testing in simulated environments. Symptoms consist of nausea, disorientation, and a visual disruption. The risk is minimal because of the short duration of each session within the simulated environment. If you experience any of the symptoms mentioned, please tell the researcher and remain seated until the symptoms subside.

Benefits: We cannot promise any benefits to you or others from your taking part in this research. However, possible educational benefits include a better understanding of automotive steering systems.

Compensation: You will be compensated $10 per hour of the session OR course credit at the discretion of your professor. For paid participants, a receipt of completion will be provided at the end of the session, which may be redeemed at the IST SONA cashier located on the 3rd floor at 3100 Technology Parkway, Orlando, FL 32826. For credit participants, credit will be awarded on the UCF Psychology SONA System upon completion of the study and will be applied as course credit at the discretion of your course professor. If you choose not to participate in the study at this time, then you will not receive compensation. If you provide consent to participate and later withdraw or are dismissed, you will be compensated only for the time you participated.

Confidentiality: We will limit access to data collected in this study to people who have a need to review this information. We cannot promise complete secrecy. The principal investigators, co-investigators, and research assistants working on this project will have access to your data. Data will be secured in locked cabinets at the Institute for Simulation & Training (IST) according to UCF IRB protocol. Please note that your name will not be associated with any of the data collected during this study. Once you sign this Informed Consent document, it will be kept in a locked cabinet separate from your data.

Study contact for questions about the study or to report a problem: If you have questions, concerns, complaints, or think the research had a negative impact on your well-being, contact the Principal Investigator, Dr. Petros Xanthopoulos at Petrosx@ucf.edu or 407-823-5218 or the Co-Investigator, Michael Xynidis at mxynidis@ist.ucf.edu or 407-551-0589.

IRB contact about your rights in the study or to report a complaint: Research at the University of Central Florida involving human participants is carried out under the oversight of the Institutional Review Board (UCF IRB). This research has been reviewed and approved by the IRB. For information about the rights of people who take part in research, please contact: Institutional Review Board, University of Central Florida, Office of Research & Commercialization, 12201 Research Parkway, Suite 501, Orlando, FL 32826-3246 or by telephone at (407) 823-2901. You may also talk to them for any of the following:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You want to get information or provide input about this research.

____ _______________

Signature Date

____

Printed Name

APPENDIX C: DEMOGRAPHICS QUESTIONNAIRE

Participant ID #:__________

Demographics Questionnaire

1. **Age**: ______
2. **Race/Origin/Ethnicity with which you identify:** ____
3. **Sex** (Circle one): FEMALE MALE
4. **Which is your predominate hand?** (Circle one): RIGHT LEFT
5. **Are you color blind?** (Circle one): YES NO
6. **Do you have normal, or corrected vision?** (Circle one): NORMAL CORRECTED
   If CORRECTED*, are you wearing corrective lenses now?* (Circle one): YES NO
7. **Are you in your normal/usual state of health?** (Circle one): YES NO
   If NO*, briefly explain*: ____
8. **Approximately, how many hours of sleep did you get last night?** ______________________________
9. **What is your highest level of education completed?** (Circle one):
   High School or equivalent Less than 4 years of college Completed 4 years of college
   More than 4 years of college Other: ____
10. **When did you use computers in your education?** (Circle all that apply):
    Grade school Jr High High school Technical school College Did not use
11. **How would you describe your degree of comfort with computer use?** (Circle one):
    Poor Fair Average Above average Proficient
12. **How would you describe your degree of comfort with driving a motor vehicle?** (Circle one):
    Poor Fair Average Above average Proficient
13. **How many years have you been a licensed driver?** (Circle one):
    Fewer than 3 3 - 5 5 - 10 10 - 15 More than 15
14. **Can you operate a manual stick-shift transmission?** (Circle one): YES NO
15. **How many times entering as a driver/passenger in a recreational or competitive driving event (rally, race, etc.)?**
    Driver: __________ Passenger: __________
16. **How many times have you been a driver/passenger in a car crash where anyone required hospital care?**
    Driver: __________ Passenger: __________
17. **How many times have you been a driver/passenger in a car crash where a vehicle required towing (disabled)?**
    Driver: __________ Passenger: __________
18. **For each of the following questions, circle the response that best describes you. How often do you:**

ride as a passenger in a vehicle?	Daily	Weekly	Monthly	Every few months	Rarely	Never
drive a vehicle?	Daily	Weekly	Monthly	Every few months	Rarely	Never
use a game controller?	Daily	Weekly	Monthly	Every few months	Rarely	Never
drive a remotely-controlled toy or vehicle?	Daily	Weekly	Monthly	Every few months	Rarely	Never
play computer/video games?	Daily	Weekly	Monthly	Every few months	Rarely	Never
use a computer?	Daily	Weekly	Monthly	Every few months	Rarely	Never
use a smart-phone?	Daily	Weekly	Monthly	Every few months	Rarely	Never

APPENDIX D: MOULOUA USABILITY SURVEY

Participant ID#: _____
Condition (A/B): _____

STEERING SYSTEM USABILITY QUESTIONNAIRE*

Instructions:

Below are general and specific statements regarding the system with which you just interacted or operated. Following each question, please circle the most appropriate answer regarding your experience. If none applies, then circle "n/a".

SIMPLICITY

1. The current steering system is easy to use.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

2. The current steering system is very friendly to use.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

3. The current steering system does not require a lot of effort to use.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

4. The current steering system does not allow me to recover from mistakes easily.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

5. The current steering system does not require written instructions to use.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

6. The current steering system is not complex.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

7. The current steering system requires formal training.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

*Adapted from: Mouloua Usability Questionnaire (Rivera, 2010) and Usefulness, Satisfaction and Ease of use (USE) Usability Questionnaire (Lund, 2001)

8. The current steering system can be used by only computer-literate people.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

USEFULNESS

9. This steering system is very useful when performing this task.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

10. This steering system is not effective for me to accomplish what I need.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

11. This steering system saves me time or effort when performing this task.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

12. This steering system does not meet the needs to perform this task.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

13. This steering system meets my expectations.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

FUNCTIONALITY

14. This steering system allows me to accomplish the functions I need to perform this task.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

15. This steering system does not function the way I have expected.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

16. This steering system works very well.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

17. This steering system lacks my expected level of function.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

CONSISTENCY

18. The design of this steering system is very consistent with what it should be.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

19. This steering system always works the same way.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

20. The interaction with this steering system always requires the same techniques.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

21. The initial knowledge needed to use this steering system does not change very often.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

22. This steering system does not always involve the same interaction techniques.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

PROFFICIENCY

23. This steering system does not require special knowledge to use it.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

24. This steering system requires only minimal computer knowledge to use.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

25. This steering system is not easy to learn.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

26. It is very easy to remember how to use this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

27. This steering system is very quick to learn.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

28. This steering system does not require special skills.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

SATISFACTION

29. I am not satisfied with this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

30. I am satisfied with the aesthetic of this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

31. I would definitely use this steering system again.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

32. I would not like to have this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

33. I would not recommend this steering system to my friends.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

BEHAVIOR

34. I get very frustrated when I use this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

35. This steering system does not make me anxious when I use it.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

36. I get very stressed when I use this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

37. I feel I have learned a lot from using this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

38. I feel very relaxed when I use this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

39. This steering system saves me a lot of time when I use it.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

40. This steering system saves me a lot of effort when I use it.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

NEED FOR IMPROVEMENT

41. This steering system does not need to be improved.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

42. Making changes to this steering system would help me perform this driving task more easily.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

43. This steering system should look different to be acceptable.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

44. This steering system needs to be re-designed to function better.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

45. I would prefer this steering system for allowing me to learn techniques faster.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

46. This steering system should help me remember how to perform this driving task.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

47. This steering system should be more fun to use and not so stressful.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

MENTAL MODELS

48. This steering system does not fit well with my way of thinking when perform this driving task.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

49. I very-often had a hard time figuring out how the steering system was working.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

50. It is not very clear to me how to recover from my errors when I use this steering system.

Completely Disagree	Disagree	Somewhat	Agree	Completely Agree	n/a

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