Personalizing Steering Experience
Using Steer-by-Wire Systems

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Conventional steering systems rely predominantly on movement of interlinking mechanical components in the steering system to initiate steering and in those systems the forces generated in moving the road wheels are transmitted back to the steering wheel through a mechanical shaft known as the steering column. The driver provides an input on the steering wheel to generate an output, which is the movement of the road wheels. The forces generated in moving the road wheels are fed back to the steering wheel through the steering column. The feedback generated on the steering wheel provides information for directional control to drivers. The feedback also contributes to a feeling of steering referred to as steering feel. Steer-by-wire systems (SbW) are state-of-the-art advanced steering systems where the mechanical components and linkages such as the steering column are replaced by electromechanical actuators to enable the driver to steer a vehicle. Hence in SbW systems, the feedback from the road wheels is no longer transmitted “naturally” to the steering wheel and results in loss of steering feel. One of the challenges with SbW systems is therefore the generation of “natural” steering feel. But with there being different cars offering different steering feels and there being individual factors influencing preferences, what is “natural” to one driver may not necessarily be “natural” to another driver as it may depend on the steering feel that a driver is most familiar with and also on individual factors. Hence the challenges in developing “natural” steering feel translate into understanding “What is an acceptable or optimal steering feel for drivers?” and “How can this be provided with SbW systems?” This dissertation presents driving simulator and SbW prototype vehicle studies to tackle these challenges and come up with recommendations for SbW system design.

Individual Preferences

One of the important components of steering feel is the feedback torque generated on the steering wheel. The feedback torque is to be overcome by the driver in steering the vehicle and the effort made in overcoming it is known as steering effort. Steering effort has been continuously reduced with various steering assist mechanisms but drivers are not provided with flexibility in adjusting the effort in most passenger cars. A driving simulator study was therefore conducted to investigate the needs for adjustable steering effort settings based on individual differences. The study used four different speed-regulated simulated driving environments to study preferences for steering effort. The study also investigated the effect of gender on preferences for steering effort. The findings from the study revealed that there is indeed an effect of individual difference in preference for steering effort but gender did not have a significant effect. Results from the study pointed to the need for more flexible...
systems where drivers can adjust their steering effort profiles. The study further hinted that Comfort and Control were important factors which influenced individual preferences.

**Comfort and Control**

The second experimental study which was also conducted on a driving simulator was aimed at studying the factors Comfort and Control in more detail. The study explored the underlying subjective attributes associated with Comfort and Control and also how the perceived level of these two factors varied with different levels of feedback torque which in turn produced different levels of steering effort. Underlying subjective attributes were identified through a pilot study and a questionnaire was developed to quantify Comfort and Control with six different levels of feedback torque. Results of the study indicated that Comfort and Control were interdependent and had several underlying attributes. There were therefore no separate optima for Comfort and Control in relation to feedback torque but the perceived level of Comfort and Control was low when the feedback torque was 0 Nm (no feedback) and when the feedback torque was greater than 5.6 Nm.

**Feedback Torque Levels and Driving Performance**

While there are individual differences in preferences for steering effort, settings cannot be offered based on preferences alone as steering is a safety critical task where performance also needs to be considered. Performance was studied for six different feedback torque levels using standard performance metrics such as Standard Deviation of Steering Wheel Angle (SDST), Standard Deviation of Lane Position (SDLP), Mean Driving Speed (MDS) and Steering Wheel Reversal Rate (SRR). Driving data logged in the simulator were used to compute SDST, SDLP, MDS and SRR. Results from data analyses showed that drivers are able to quickly adapt to different levels of feedback torque (even with levels rated poorly in perceived Comfort and Control) maintaining similar levels of performance. However, in the absence of feedback torque (0 Nm) performance is adversely affected.

**Cognitive Load and Adaptation to Feedback Torque Levels**

It was hypothesized that drivers were able to quickly adapt to different levels of feedback torque by giving more mental effort, that is, by mobilizing extra cognitive resources. If this hypothesis is correct, introducing a secondary task would impede the adaptation. To test this hypothesis, performance with the six different levels of feedback torque combined with a secondary task was studied in a driving simulator. In addition to performance with the secondary task, baseline measures (performance without secondary task) were also obtained and mental workload was measured using the Rating Scale for Mental Effort (RSME scale). While results showed that the combined task of driving and performing the secondary task was perceived to be more difficult than driving without the secondary task, performance across the six different feedback torque levels did not change except when
there was no feedback (0 Nm). In other words, even with the secondary task which added mental workload, drivers were still able to quickly adapt to the different levels of feedback torque. And here again when there was no feedback torque performance appeared to be adversely affected.

**Mapping Subjective Experience Attributes to Physical Steering Parameters**

This dissertation also provides two studies conducted on a prototype SbW test vehicle where the aim is to map subjective experience attributes to physical steering parameters. It is known that there are experiences other than force which can influence steering feel. To develop SbW systems, an understanding of other subjective experience attributes is also required. Apart from gaining an understanding, if steering feel is to be personalized according to one’s own needs and requirements, we need to know how the physical steering parameters which can be varied in a steering model map onto subjective experience attributes. Such a mapping is provided based on results from the two studies to enable designers to provide drivers with a defined steering feel or opportunities to select their own desired steering feel.

**Research Relevance**

The research aims to contribute towards further development of advanced SbW steering systems which are continually being developed to improve the safety, operational efficiency, robustness and also the user experience. Based on the experimental studies, requirements for SbW systems where steering experiences can be personalized are outlined. Recommendations for HMI using which drivers can interact with the steering model are also presented.
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“Cars represent an excellent example of a profound technology that has woven itself into the fabric of everyday life until it is virtually indistinguishable from it” (Walker, Stanton & Young, 2009). Cars are found everywhere today and are driven so easily by all types of individuals, that we seldom pay attention to the technological sophistication of a car. A car has several systems onboard such as steering, suspension, engine control and so on, which enable the task of driving. With the growth of technology, these systems have integrated more electrical technology to expand their operational capabilities and also improve system efficiency, safety and driving experience – the reasons which car manufacturers state are the fundamental drivers for integrating computerized electrical systems (Walker et al., 2009).

One of the technological advances is by-wire technology. By-wire technology radically changes the way in which subsystems of vehicles are built and operated. Operation by-wire eliminates the need for mechanical interlinking of the different subsystems. These mechanical linkages are then replaced with sensors, controllers and actuators which are controlled electrically. Elimination of mechanical interlinking removes inter-dependencies between subsystems and operation can be done through a computerized model that will control systems (Bretz, 2001). Exerting control via a computerized model offers advantages in allowing systems to operate with increased flexibility which would otherwise not be possible with mechanical connections. For instance, the suspension system can be operated independently to help the driver from experiencing centrifugal force (the force that pushes the driver away from the direction of vehicle turn). Furthermore, there can be at least 15 kg reduction in weight of the car with by-wire technology thus leading to improvement in engine efficiency (Sanders & Baldwin, 2001). In comparison to earlier vehicle technology, systems operated by-wire enable easy integration of Advanced Driver Assist Systems (ADAS) which serve to assist the driver in specific contexts such as during lane departures, cooperative driving, collision avoidance and so on (Kauffmann, Millsap, Murray & Petrowski, 2001; Walker et al., 2009). By-wire technology therefore provides significant advantages and increased flexibility in comparison to earlier systems. Developing systems using by-wire technology can result in improving driver experience as these systems can model system response accurately based on the needs and requirements of drivers. Walker et al., (2009) state that there are inherent challenges here in understanding how drivers interact with different systems. This thesis focuses on addressing such challenges to improve the experience for the driver with Steer-by-Wire (SbW) steering systems.

1.1. Steer-by-Wire Systems

The steering system is a critical component of the vehicle which is used to control lateral position. It is a closed loop system (Metz, 2004) where the driver provides input on the steering wheel to generate desired movement of the road wheels (tyres). Forces at the tyre-road surface generate feedback contributing to the driver’s sense of control over the road wheels. The feedback from the road wheels that is transmitted through the steering system to the steering wheel is referred to as steering feedback. The driver closes the loop by using
the feedback to decide on further input to the steering wheel. The characteristics of the system generated feedback contribute to a subjective experience known as steering feel (Yao, 2006; Newberry, Griffin & Dowson, 2007). Steering systems have continuously evolved to improve the steering feel by introducing several innovative interventions such as power assistance systems. Power assistance systems enable drivers to avoid high amounts of physical exertion which would otherwise be required from drivers to steer the road wheels (Nakayama & Suda, 1994). Power-assistance systems however did not alter the basic structure of the steering system. The steering feedback is transmitted via the steering column, a mechanical shaft, which is coupled to the steering wheel through an intermediary gear mechanism. Since the structure of power-assistance system did not remove the physical linkage between the steering wheel and road wheel, the feedback in such systems is still deemed to be naturally transmitted. However, with a SbW steering system, there is no requirement for such a linkage and furthermore removal of the steering column increases driver safety in head-on collisions, reduces weight and offers additional space (Sanders & Baldwin, 2001). However, with the loss of the steering column, feedback is no longer naturally transmitted. “Natural” feedback needs to be generated instead with electromechanical actuators controlled by parameters of a steering model. Control via a steering model is a solution to transmit feedback in the way that was normally done and deemed ‘natural’. As a side effect, there is now the unique opportunity for designers to develop new steering settings which can further enhance the driving experience. The feedback design for SbW system therefore presents unique challenges and opportunities (Yao, 2006; Williams & Sherwin, 2009).

1.2. Research Challenges

Steering system design and operation are different depending on the manufacturer. The feedback can be different due to the hardware used by the manufacturer and the way in which they are tuned. Hence steering feel can vary from vehicle to vehicle. So the challenge of designing “natural” feedback is a bit more complicated as it is dependent on what car drivers are used to driving. The question then arises as to “What is an acceptable or optimal steering feel?” and how this can be generated using a SbW system. Studies (Green, Gillespie, Reifeis, Wei-Haas & Ottens, 1984; Bertollini & Hogan, 1999; Barthenheier & Winner, 2003; Newberry et al., 2007) have shown earlier that there are individual differences in preferences for steering feel. Systems prior to SbW did not offer designers and engineers a high degree of flexibility to provide drivers an opportunity to adjust steering feel. Hence drivers are required to adapt to the feel generated by steering system design of the manufacturer. However, recognizing the need of drivers to adjust their steering experience, manufacturers offered multiple preset settings on their high-end vehicles. Examples of a setting suite can be Comfort and Dynamic which the driver can alternate between (OnCars.com, 2014). Such settings can result in distinct steering experiences, but may not necessarily offer an experience that the driver desires. To improve steering feel experience,
drivers need to be given the opportunity to vary specific elements of steering feel that they can comprehend. Such an opportunity can be provided through a Human Machine Interface (HMI) of SbW systems. An HMI design is however not straight-forward as it requires an understanding of several human factors issues. The car is a product designed for general use and this means that there are all kinds of individuals with different capabilities and limitations who can drive a vehicle. The HMI design must therefore ensure that it satisfies the needs and requirement of a wide range of individuals. Finally, options offered by an HMI should be mapped to parameters in the steering model. The options of the HMI must therefore correspond to specific subjective experience attributes that can be manipulated through the steering model. Such understanding needs to be gained by first investigating the subjective experience space for drivers and mapping them to parameters that can be modified in a steering model. There are therefore multiple challenges involved in exploiting the design flexibility of SbW systems to offer drivers settings that can be modified to offer a natural or desired experience.

1.3. Research Goals and Questions

To address and overcome the above mentioned challenges, several research studies with multiple test beds, diverse set of drivers are likely requires and these require significant amount of time and resources. With constraints on both time and resources, the doctoral research presented in this thesis has narrowed down the focus area into four questions presented in this section. Answers to these questions will result in significant contributions towards expanding our knowledge on steering feel, driver preferences and also how drivers perceive different elements of feedback generated by the system. The understanding will then be used to make recommendations for feedback design in SbW systems and the HMI using which drivers can manipulate steering feel.

One of the key elements of steering feel is the feeling of force as a result of steering wheel feedback torque (Yao, 2006, Gualino & Adounkpe, 2006; Newberry et al., 2007; Williams & Sherwin 2009) and our research began by focusing on this element. Limitations earlier on in availability of test-equipment to study other aspects of steering feel made us thoroughly focus on feedback torque and subjective experience of force. Research began by observing continuous efforts made by manufacturers to reduce the steering wheel feedback torque to reduce steering effort. And with most vehicles offering only a single setting, investigation was done to check whether the force component matched driver’s preferences. The investigation led to defining our first goal which was to study the impact of individual differences on preferences for steering effort. The second research goal was to study factors which influence preferences for steering effort as we wanted to gain further insight into individual preferences. While an understanding of preferences and their influencing factors is important, in order to define system requirements, it is also important to study
performance. And so our third goal was to study performance with different steering settings.

As mentioned earlier, steering feel encompasses aspects other than force. These other aspects also need to be investigated, more specifically, we need to know how they can be varied to create desired subjective experiences for the driver. The fourth and final goal was therefore to explore the subjective experiences and map them to specific parameters in a steering model. Such a mapping is required to design the HMI through which drivers can adjust steering parameters. Without the mapping, drivers would have to have expert knowledge of steering parameters and their behavior. Such understanding cannot be expected from normal drivers.

The four research goals were formulated into four broad research questions that are addressed in this thesis:

1. What is the impact of individual differences on preferences for steering effort?
2. What are the factors influencing individual preferences for steering effort and what impact does feedback torque have on these factors?
3. How do changes in steering settings affect driving performance?
4. What is the mapping between parameters in the physical space and steering feel attributes in the subjective space?

1.4. Research Approach

Scientific literature was examined and was used as the theoretical base from which exploratory and confirmatory research studies were designed and conducted to achieve research goals. In total, five research studies with regular drivers as test-participants were conducted. Three studies were conducted in a fixed-platform driving simulator and two studies were conducted in a prototype SbW test-vehicle. The driving simulator was the first available test equipment and hence studies and methodologies suitable for simulator experiments were designed. The first study was both confirmatory and exploratory in approach as we wanted to confirm the need for continued development of variable power assist steering and also to explore differences in driver preferences. The study led us to conclude that new hardware and steering models had to be developed for enhancing capabilities of the simulator as suitable test equipment for SbW research. The second study also followed a combined confirmatory and exploratory research approach to understand factors influencing steering effort preference. While hypotheses on different optima for influencing factors formed the confirmatory part, the methodology focused on exploring the influencing factors and their relationship to steering effort. The third driving simulator study followed a confirmatory approach to test a hypothesis that was formulated as an
explanation for performance results from the second study. Conducting studies in the driving simulator offered significant advantages in developing a controlled test environment where driving scenarios could be modified to suit needs of the study. The driving simulator was also a very convenient and easy-to-use test platform. On the flipside, the driving simulator was not built for SbW research and several modifications had to be made in incorporating a steering model which was controllable in real-time. The driving simulator was also fixed-base and therefore it was unable to allow drivers to experience the lateral acceleration forces that they would normally feel in a real car. A pilot study conducted also showed that even with a realistic steering model where different parameters could be modified, participants were only able to experience changes in magnitude of Force. Hence research studies to answer the fourth research question (which concerned aspects other than force) had to be tested using alternate equipment.

While research studies were being conducted in the driving simulator, a prototype SbW test car was being developed by the Department of Mechanical Engineering at Eindhoven University of Technology by ir. Tom van der Sande, a PhD candidate also recruited for the VERIFIED project. The car became test-ready for experimental purposes in the beginning of 2012. Several test-runs were performed to test operational capabilities. The prototype vehicle offered significant advantages in realism over the simulator and drivers were able to experience aspects of steering feel other than force. However, conducting studies using the prototype offered less experimental control than the simulator. Furthermore, safety considerations had to be given to participants and suitable test tracks needed to be identified and used. With the simulator deemed not suitable for exploring the subjective space and mapping emerging subjective experience attribute to physical steering parameters, the test car was used to conduct the final two studies. The first study conducted on the prototype vehicle was exploratory in that the subjective space was explored and mapped to parameters of the steering model. The second study conducted on the prototype vehicle had a confirmatory approach where the subjective space and mapping were tested at higher speeds.

Performance results from the prototype SbW vehicle were compared against performance findings from the simulator study. As the prototype SbW vehicle was realistic and tests were conducted outdoors on test-tracks, the comparison was used to validate findings from the driving simulator studies.

1.5. Thesis Outline

Five experimental studies conducted to meet research goals are presented in this thesis. Since the experimental studies are focused on steering, which is a complex and safety-critical task, readers are presented with a detailed understanding of steering systems from the human factors perspective in Chapter 2. In addition, Chapter 2 provides an overview of the development of steering systems leading up to SbW systems to highlight technological
advancements in this area and also the unique challenges SbW systems present moving forward.

Chapter 3 presents the first experimental study conducted on the driving simulator to answer the first research question. The study offers insight into the impact of individual differences in preferences for steering effort. The study investigates individual preferences in different speed-regulated driving environments for steering environment and studies impact of individual factors such as gender on preferences. Chapter 4 of this thesis presents significant upgrades that were carried out on the driving simulator to make it a more suitable platform for conducting SbW research.

Chapter 5 presents the second experimental study conducted on the driving simulator to answer the second and third research question. The study specifically focuses on two factors (Comfort and Control) which were found to influence preferences for steering effort. The study explores these two factors and their relationship with different levels of steering effort. Using the same study, driving performance with different feedback torque levels is also investigated. Chapter 5 also offers more insight into what is deemed “natural” and “normal” by drivers when it comes to feedback torque. Chapter 6 builds on the performance findings from Chapter 5 and studies performance with different feedback torque levels when cognitive load is increased.

Chapters 7 and 8 each present a study conducted in the prototype SbW vehicle. The studies presented in these chapters aim to answer the fourth research question which was to explore subjective experience and map them to parameters in a steering model. While Chapter 7 presents a study conducted at low speeds, Chapter 8 presents a study conducted at higher speeds on a test-track. Chapters 7 and 8 also help to answer the third research question regarding performance. Apart from investigating performance in which aspects other than feedback torque were varied, the studies also assist in checking the validity of performance results from simulator studies presented in Chapters 5 and 6.

Conclusions from all the five experimented studies are discussed in Chapter 9, the final chapter of this thesis. Based on findings, general system recommendations for SbW system are made. Suggestions for HMI design on which drivers can make their personal preferences for steering feel are also presented. Chapter 9 also revisits the research question defined in the introduction chapter and concludes with reflection and directions for future work.
CHAPTER 2

Steering System Overview & Emergence of Steer-by-Wire
2.1 Introduction

Driving is a complex task that involves 1,700 individual tasks (McKnight & Adams, 1970) of which many are today performed by as many as 30 on-board computers (Walker et al., 2009). The human driver today performs three main tasks 1) Vehicular control 2) Route Navigation and 3) Hazard Avoidance (Marsden & Stanton, 1996). Steering is a critical vehicular control sub-task performed by drivers in establishing vehicular control and hazard avoidance. This chapter discusses steering in greater depth to provide an understanding of how the task has evolved to improve the experience for the driver. System developments are also discussed briefly to highlight the flexibility and advantages of Steer-by-Wire (SbW) steering systems.

2.2 Steering

Steering is a task performed by rotating the steering wheel. Rotation of the steering wheel results in actuation of the steering mechanism involving components such as steering column, cardan joint, rack-and-pinion, and tie-rods steering arms connected to the road wheels’ (tyres’) kingpins (Toffin, Reymond, Kemeny & Droulez, 2007). A high-level overview of a basic steering system is shown in Figure 2.1.

Figure 2.1. High-level overview of a basic steering system. (from www.answers.com/topics/automotive steering, 2014)

As the driver rotates the steering wheel, forces are produced at the road-tyre contact surface. Based on system design, the forces produced are dependent on the self-aligning moment based on steering geometry, vehicle lateral acceleration*, steering angle and
vehicle speed. The forces produced at the road-tire contact area are then transmitted to the steering wheel through the steering mechanism as feedback torque. The forces that are fed back to the steering wheel contain information regarding instantaneous dynamics of the vehicle and this aids the driver in maintaining directional control (Gillespie, 1992; Gualino & Adounkpe, 2006). The feedback is perceived through proprioceptor sensors in the body. Since feedback torque is also dependent on lateral acceleration, drivers can use the feedback in addition to visual information to process required steer based on curvature of trajectory (Gillespie, 1992). From a driver’s perspective, a model of steering feedback can be as shown in Figure 2.2. The system is an input/output mechanical system with two inputs and two outputs: 1) Input from driver to steering wheel resulting in Output from the steering mechanism to push the tires and 2) Inputs from the forces on the tires resulting in Output force fed to the steering wheel as feedback torque.

![Figure 2.2 Steering feedback model](image)

While feedback torque is important due to reasons mentioned above, there are also other characteristics defined by the steering mechanism that are perceived by the driver which not only aid in proprioception but also to the overall steering experience. A well-designed system, according to Cho (2009) needs to produce good steering output with regard to response, feedback, on-center feel, steering torque build-up and steering returnability.

All of these characteristics can be varied in a steering system to generate different steering and driving experiences for the driver. In many studies (Yao, 2006; Newberry et al., 2007; Williams & Sherwin 2009), the prime component associated with steering feel is the

*Lateral Acceleration is the acceleration created when a vehicle corners and that tends to push a vehicle sideways.*
feedback torque characteristics of the system. While manufacturers have their own designs, the automotive industry had adopted several mechanisms to adjust the feedback torque profile. These mechanisms have evolved over the years and an overview of them will now be presented to point out the continuous focus on improving the driving experience for the driver. We will then discuss how limitations and evolving needs have led to SbW. The chapter will conclude with specific human factors challenges addressed in this thesis.

2.3 Power Assisted Steering

Figure 2.1 showed a basic steering system. In such a system the driver has to overcome the feedback torque and mass of the components through muscular force. While the feedback is direct, driving for long periods along a curvy trajectory can lead to considerable physical exertion (Mathews & Desmond, 2002). As there is continuous torque build-up with increasing steering angle, steering in roads where frequent turning is required can be strenuous. In our test-vehicle we were able to observe that without power-assistance, the forces in a mid-sized sedan can reach up to 15 Nm which translated into 15 kilograms of force applied over a length of 10 centimeters. Such amounts of forces are high and place high physical demand on drivers with limited muscular strength. Driving for sustained periods with such heavy forces can be difficult.

Driving is a critical task which includes hazard avoidance as stated in the introduction. There is therefore a high degree of control required by the driver. While driving on highways at high speeds, the driver can be involved in a critical hazard avoidance situation such as collision avoidance. In such a scenario the driver must execute two sharp turns similar to a double-lane change test; a sharp first turn to avoid the impending collision and a sharp reversal of the steering wheel to stabilize the vehicle. These sharp turns can be only executed if the driver is physically capable of doing them. Even if the driver is capable, such critical scenarios occur at high speeds requiring a high degree of precision. But requirement of extremely high forces from the driver (such as those occurring when there is no power assistance) can lead to understeer, where the driver attains less than desired steering angle. Understeer in a safety-critical situation (Liebemann & Fuehrer, 2007) can lead to collisions. Owing to reasons of physical discomfort and control, automotive manufacturers first introduced assist mechanisms in heavy vehicles such as trucks as truck-drivers drive for longer periods than the average driver. The assist mechanisms reduced physical exertion by offering additional support to drivers. Slowly they were introduced in passenger vehicles with assistance to drivers being provided through hydraulic and electric power.

2.3.1 Hydraulic Power Assist (HPA) Steering

Hydraulic Power Assist (HPA) mechanisms were first introduced in traditional steering systems. The basic structure of a HPA steering system is shown in Figure 2.3. In comparison with Figure 2.1, it can be seen in Figure 2.3 that there is addition of hydraulic components
such as a hydraulic fluid tank and a high pressure pump. The entire steering gear mechanism is provided with a casing to allow flow of hydraulic fluid.

**Figure 2.3. Power Steering System** (from www.answers.com/topics/autotmotivesteering, 2014)

When the steering wheel is rotated by the driver, a torsion bar attached to it is also twisted to indicate how much hydraulic power assistance is required. The torsion bar is a mechanical force gauge connected to the hydraulic fluid inlet valve. The torsion bar mechanism can be seen in Figure 2.4. So when the steering wheel is rotated, high pressure hydraulic fluid assists the driver in applying force on the road wheel which continuously opposes the movement due to self-aligning forces. By offering assistance, there is considerable reduction in physical effort and improvement in comfort. The amount of power assistance offered is dependent on the stiffness of the torsion bar. If the stiffness is very high, then the driver receives less assistance and if it is low, the driver receives more assistance. Increasing torsion bar stiffness can also improve the feel of the road surface for drivers as the vibrations occurring at the tyre-road surface contact are not masked by the assistance provided by the system.
The stiffness of the torsion bar and power assistance are entirely dependent on the manufacturers and their specification for the system and components. There is no uniform standard adapted on the amount of assistance that is to be offered and hence the feedback experience varies depending on the manufacturer. While it may seem that increasing power assistance will lead to increasing comfort, there can also be problems in overdoing the assistance. One is that proprioception can be affected within the driver with most of the natural feedback from the system being masked with the assistance as a consequence. The second issue goes back to control. Let us reconsider the collision avoidance scenario discussed for understeer. When there is extremely low feedback, it can lead to oversteer conditions. Oversteer is when the driver exceeds desired steering angle input over a period of time. With oversteer, the driver might be successful in avoiding a collision with a vehicle in the same lane, but can overcompensate and lose control in stabilizing the vehicle. Furthermore, oversteer can lead to saturation in movement of tyres and lead to undesired oversteer characteristics. At high speeds, oversteer may cause rollover of the vehicle (Hac, 2002). Finally, action to counteract oversteer may lead to oscillation causing further instability.

As HPA continued to evolve, so did computer systems and the growing use of on-board computerized systems to optimize system performance. The on-board computers in a vehicle contain a mathematical model of components in the system and control output based on system state and driver input. A steering model contains an algorithm for steering system operation that can control system output based on input from the driver to the steering wheel and also the feedback from the system to the driver. The steering model can therefore control power assistance based on steering angle and this was done with early
computerized systems. Since power assistance aids quick and easy maneuvering, which usually translates into short displacement of the steering wheel, the assistance was high for shorter displacements. However, there was continuous torque build-up (where assistance was lowered) to ensure that drivers did not oversteer. As sub-systems such as steering were beginning to be interlinked with engine control, the model included more parameters to improve driving experience. Studies by Green et al., (1984) and Bertollini & Hogan (1999) stated that steering models needed to account for driving speed as well to remove undesirable characteristics. Earlier versions of the hydraulic-pump were of the positive-displacement type, where the rate of flow of hydraulic fluid is proportional to the speed of the vehicle. This meant that when driving at high speeds, the steering system would increase steering assistance and at low speeds, the steering system would decrease steering assistance. Such settings can lead to oversteer at high speeds and understeer at low speeds. Steering systems then added an electronic flow control valve which was factored into the steering model along with speed to ensure that 1) increased assistance was offered at low speeds to assist drivers in making turns easily and 2) reduced assistance was offered at higher speeds to prevent drivers from making unintentional lane corrections. This type of assistance is known as variable-assist power steering (Nishikawa, Toshimitsu & Aoki, 1979).

2.3.2 Electronic Power Assist (EPA) Steering

HPA systems continued to develop with integration of electric controls of its components. However, there were certain limitations which could only be overcome with a different type of assist mechanism. In HPA systems, the hydraulic unit consumed engine power leading to reduced vehicle efficiency. Maintenance was also not easy with HPA systems and there were several component additions which increased vehicle weight and further affected efficiency. This then led to the development of Electronic-Power Assist (EPA) systems. While hydraulic units provide power assistance in HPA systems, a programmable electrical motor provides assistance to the driver in EPA. Depending on the type of motor, precise control is possible to improve vehicle efficiency. The assistance with EPA can also be easily controlled.

Apart from being able to vary assistance based on steering wheel angle and driving speeds, these systems were also capable of varying the steering gear ratio. The steering gear ratio is the ratio of the required steering wheel angle to the resultant road wheel angle. Most cars maintain a ratio between 17:1 and 20:1. If say the steering gear ratio is 18:1, an 18 degree rotation of the steering wheel is required to produce a 1 (one) degree displacement of the road wheels. A higher steering ratio would therefore translate into decreased system directness while a lower one would translate into increased system directness. The torque feedback mapping with steering wheel angle will therefore vary with changes in steering gear ratio. With a lower steering gear ratio, the displacement of the steering wheel is less and displacement of the road wheels is high compared to a higher steering gear ratio; therefore the system generates higher feedback torque for the same steering wheel angle in
a system with a lower steering gear ratio compared to a system with a higher steering gear ratio. A Variable Gear Ratio (VGR) system would therefore modulate driver input on the steering wheel based on system design. Such systems were first introduced in early 2000s by automotive manufacturers (from Honda Worldwide, 2000). In 2002, BMW made further advancements on VGR and developed an Active Steering system. Active Steering models vary the gear ratio and power assistance based on driving speed and steering angles with the aim of providing an experience than maximizes optimum handling comfort and system efficiency (Mammar, Sainte-Marie & Glaser, 2002).

The relationship between speed, steering angle and feedback torque with EPA is shown in Figure 2.5. The 3-dimensional map shows that the torque is varied based on speed and steering angle. Large steering wheel angle displacements occur during parking, reversing and sharp cornering maneuvers which are done at lower speeds and to ensure the driver is able to turn freely, the torque at these speeds are lowered. However, at high speeds, driving usually requires making smaller displacements of the steering wheel because large displacements at high speeds may lead to unstable driving situations. Hence, the torque is increased at high speeds to prevent the driver from making large displacements to ensure improved perception of stability and safety of the vehicle (Kim & Song, 2002).

In the overview presented thus far, it can be seen that steering experience provided by steering systems has continuously changed through technological advancements which aim to improve efficiency, comfort, safety and the driving experience. Unlike earlier steering systems which were controlled only with driver input, steering systems today make use of computerized mathematical models which control the dual input-output steering system. The discussion so far shows that the model controls feedback torque to the driver based on the power assistance. The experience can be modified for handling comfort by modeling
power assistance (varied by a parameter known Power Assistance Gain) as a function of Steering Wheel Angle and Speed of the vehicle. In most steering systems there is a linear build of force, meaning as the driver steers further away there is less assistance offered to prevent the driver from oversteering. This linearity in power assistance can also be varied in the system. That is the assistance can profile can assume even non-linear profiles to alter steering feel and this is done by varying the power assistance to steering wheel mapping, the mapping is commonly referred to as the boost linearity of the system. The steering feel can also be varied by the Steering Gear Ratio parameter in the model which controls a variable steering gear mechanism. The parameter alters the directness of the system. The values for these system parameters are decided by manufacturers to allow drivers to experience a defined steering feel. In some instances, the manufacturers provide drivers the opportunity to switch between settings i.e. an opportunity to alternate between presets in steering models.

In developments that have been discussed, the mechanical linkage is still present between the steering wheel and road wheels. The existing linkage means that other parameters of the steering system such as the damping of the steering wheel and steering rack are also controlled by physical mechanical components. To control steering characteristics effectively, the mechanical components need to be replaced by electromechanical actuators.

2.4 Steer-by-Wire Systems

Advancements in electrical technology allowed the automotive industry to conceptualize by-wire systems where the operation of vehicle subsystems was not limited by interlinking connections. By-wire systems enable the response of vehicular subsystems to be accurately mapped based on driver input. Safety can be improved with these systems as they allow computer controlled vehicle interventions through Electronic Stability Control (ESC). And along with safety, driving experience can also be improved with Advanced Driver Assistance Systems (ADAS) systems. Elimination of mechanical linkages can reduce weight and improve vehicle efficiency. By-wire steering systems referred to as SbW offer all the earlier mentioned advantages and also allow flexibility in programming steering controls individually. Such flexibility provides the opportunity to accurately tune steering according to driver preferences (Mammar et al., 2001; Walker et al., 2009). These preferences can vary due to individual factors and based on personal driving experiences (Barthenheier & Winner, 2003; Green et al., 1984). There are therefore a wide range of preferences and drivers can be allowed to make their choice using an HMI. Before moving to this challenge we review the state-of-the-art of SbW systems.

With the elimination of mechanical linkages, computerized control is exerted through electrical connections between individual components of the steering system. An example of a SbW system is shown in Figure 2.6. HW denotes Hand Wheel/Steering Wheel and RW denotes the Road Wheel/Tyres.
The striking feature of the steering system is the elimination of the steering column. The elimination results in loss of a ‘natural’ medium for transmitting input to the road wheel and the resultant forces at the road-tyre contact surface back to the steering wheel. The inputs and outputs will have to instead be transmitted through electrical connections. Electromechanical actuators attached to the steering wheel are now required to produce feedback torque for the driver. The actuators must also define values for damping of the steering wheel as there are no damper controls present and must also simulate stiffness as would be done with an actual torsion bar with a defined stiffness value. Electromechanical actuators are also required at the road wheel to move them based on driver input.

The entire system will have to be based on a steering model. Once the driver provides input on the steering wheel, the signals are read by the model to decide on an input for the road wheel actuators. The input here can be made dependent on steering wheel angle, vehicle speed and steering gear ratio as done with earlier systems. The input to the road wheel actuators will result in forces generated at the road-tyre contact surface. These forces have to be recorded by sensors and transmitted to the model. The steering model then will have to decide on the input to the steering wheel actuators to generate feedback torque. The feedback torque can be similar to earlier steering systems. The torque build-up can be made linear or non-linear by adjusting the boost linearity profiles. In addition, it is easy to design specific on-center steering feel for the driver when the driver is driving straight. The on-center feel contributes to a heightened sense of control over the steering wheel when the car is moving straight. The return-to-center characteristics can also be modified easily with SbW systems. The return-to-center characteristics of a steering wheel define properties on how the steering wheel returns to center after the driver loosens the grip on the steering wheel after executing a corner (Chao, 2006). The steering model in a SbW system can also be...
linked with other sub-systems and their behavior can also be modified if desired. For example the active suspension system can be programmed to individually adjust suspensions at the desired road wheel to prevent the driver from experiencing centrifugal forces during cornering.

2.4.1 Challenges with Steer-by-Wire

As can be seen from the description of the system, it is clear that a SbW system is much more flexible in operation in comparison to HPA and EPA steering systems. The flexibility ensures that designers have more freedom in designing feedback and feel of the steering wheel by manipulating parameters in a computerized steering model. By interfacing parameters of the steering model to associated subjective experience using an HMI, drivers can also be presented the option to modify their steering feel. However, reproducing feedback and customizable options present certain challenges that have to be overcome.

One of the main challenges is in ensuring that SbW systems generate ‘natural’ steering feel for a driver. Steering feel has been commonly described as the communication of tyre forces and vehicle dynamic states to the driver via the steering wheel (www.prodrive.com, 2014). Steering feel has also been described as “the perception of a complex sensation while steering a vehicle” (Rothhämel, 2013). The definition by Rothhämel (2013) relates to the perception of forces and positions through proprioception where the cereberic compares information from the vestibular system and the visual information. The perception can then vary across drivers generating different experiences in the same car for the different drivers. And with there being different types cars that generate different steering feel and drivers who perceive steering feel in different ways, ‘natural’ steering feel can be based on a driver’s experience. In addition, there are also individual differences and personal preferences that may have a role in what type of steering feel is deemed ‘natural’. Hence there is an understanding required on individual preferences and also on steering feel when steering system characteristics are modified.

In steering systems thus far, drivers are not presented with options to experience different kinds of steering feel other than few preset options in high-end luxury vehicles. So if drivers are to be provided with opportunities to exercise wide range of control over steering feel, then an understanding is required on steering feel and its contributing subjective experience attributes. And subsequently there is an understanding required on how the subjective experience attributes can be varied. With SbW systems, steering system characteristics are entirely controlled through computerized mathematical models with steering parameters. The parameter values can be modified to alter the steering feel. However, to understand which subjective experience attribute is affected with parameter changes, a mapping between the two is required. This chapter has also discussed how steering characteristics have been modified as function of speed, steering angle and so on. Investigation of steering feel must also take into account these aspects. There has been significant work done on
understanding and improving steering feel using conventional systems which can be seen in (Rothhämel, 2013). For instance studies were conducted to understand human perception with changes in steering wheel torque to gather just noticeable differences (JND) data (Buschardt, 2003). And Deperman (1989) in his investigation on subjective directional stability in passenger cars was able to identify steering effort and steering feel as two quantities used by drivers in assessing directional stability of the vehicle. While there have been numerous studies using conventional systems which has contributed to development of steering, there are limitations in existing systems that prevent drivers from being able to customize steering to their liking. With SbW such opportunities can be provided to drivers but in order to do the challenges mentioned above must be overcome.
CHAPTER 3

Individual Differences in Preferences for

Steering Effort

This chapter is based on:

3.1 INTRODUCTION

Steer-by-wire systems provide drivers with the opportunity to personalize steering settings in vehicles. Studies conducted in the past have indicated that preferences for steering effort, one of the factors which affect steering feel, vary based on individual differences including factors such as age, gender and driving style. The individual differences stem mostly from subjective findings of evaluations and comparative studies, where participants experienced different steering settings where different aspects of feedback were varied. This chapter describes an experiment conducted on a driving simulator designed with a user interface that allows participants to actively modify only the steering effort settings on the steering wheel. This setting was used to investigate the effect of gender on preferences for desired steering effort and personalization of future steering systems.

Earlier studies (Green et al., 1984; Barthenheier & Winner, 2003; Clemo, 2005) had shown that preferences for steering effort vary across individuals on a number of factors including age, gender, driving experience and driving style. A study conducted by Barthenheier & Winner (2003) illustrates some of these individual differences (based on age, gender and driving style) for preferences of steering effort, supporting the desirability for a personalized steering system. The study investigated parameters such as return-to-center moment, damping, applied torque and system delay. As part of the study, subjects compared different settings of these parameters and provided judgments concerning comfort, driving fun, safety and overall preference. Preferences were investigated as a function of driving situation (highway/country road/city road). The study revealed that preferences for steering parameters which influence steering effort and steering feel in these driving situations, varied significantly across individuals based on age, gender and driving style. The driving situations required drivers to drive at different driving speeds, thereby indicating that preferences also vary based on driving speed. Studies conducted on a moving platform driving simulator by Bertollini & Hoganl (1999) also showed that driver preferences for steering effort vary significantly based on speed and driving maneuver. However, the study did not find age, gender and driving experience to significantly affect the preferences for the settings as it did not explicitly aim to study effects of individual differences. The outcomes of the study conducted by Barthenheier and Winner (2003) confirmed those of an earlier study by Green et al., (1984), which indicated gender may affect preferences for steering effort. The automotive industry has also recognized these varied preferences and has attempted to personalize steering by providing drivers the option to reduce steering effort with a single push button that increases power assist. The amount of power assist can however not be regulated and may not meet the needs of certain drivers. Creating such scenarios where drivers’ need for steering effort are not addressed through adequate system design may
create conditions of oversteer and understeer, which may lead to potentially life threatening situations and result in roll-over of the vehicle during oversteer (Hac, 2002; Metz, 2004).

Full personalization of steering settings is not possible with existing steering systems as they are limited by technology. However, by-wire steering systems, referred to as steer-by-wire (SBW) systems, provide increased flexibility to adjust these settings (Tajima, Yuhara, Sano & Takimoto, 1999; Odenthal, Bunthe, Heitzer & Heiker, 2002; Oh, Chae & Jang, 2003; Verschuren & Duringhof, 2006). By being able to program the operating characteristics of the electromechanical actuators that replace gear mechanisms, multiple modes of operation can be defined to create personalized settings that can be controlled using a user interface in SBW systems. The user requirements for these personalized settings however are still not defined. There may be individual differences in preferences and also subjective feel elements which can influence preferences.

An experiment was therefore conducted to investigate variations in preferences related to steering feel. Given the fact that steering takes physical effort and that physical strength differs between males and females, preferences were investigated as a function of gender. In addition, since it is likely that the level of feedback torque influences perceived comfort and control, participants’ opinions about the relative importance of control and comfort were elicited and compared with their preferred level of feedback.

3.2. METHOD

3.2.1 Experimental Design
The experiment followed a within subjects design and extracted both qualitative and quantitative data. The study required participants to perform specified experimental tasks and to provide requested information and express their opinions through pre-task and post-task questionnaires.

3.2.2 Materials
A pre-task questionnaire was administered to gather participant information such as age, annual driving mileage, exposure to power steering systems and preference for steering controls. Information pertaining to the type of car used and regular driving environment were also gathered. Importance given to steering comfort and control while driving was also ascertained using a 5-point Likert rating scale.

A post task questionnaire administered on completion of the experimental tasks aimed to gather quantitative and qualitative data to assess the validity of the experimental setup and
gather information about what could additionally be done to improve steering performance. Three statements with a 5-point Likert rating scale and two open-ended questions were presented to the participants to gather quantitative and qualitative information respectively.

### 3.2.3 Equipment

The experimental tasks were performed by participants on a fixed-base driving simulator manufactured by Green Dino Technologies Limited, The Netherlands. The simulator provided a semi-immersive driving environment with a panoramic view of the driving scene as shown in Figure 3.1.

![Figure 3.1. Driving environment view on the simulator.](image)

The simulator made use of a brushed DC motor to generate reactive torque. While the steering mechanism in the simulator was programmed to provide speed based reactive torque to simulate road wheel movement, it was not suitable in its original design for the experiment. The steering feedback was therefore modified to produce variable steering torque (to be explained below), which then generated varying steering effort that could be controlled by participants using an interface on the steering wheel.

The first strategy was to work with the steering model in the simulator to produce variable feedback torque. However, the system was not flexible enough and the motor controller could not be controlled while driving to apply different feedback forces on the steering wheel. Moreover with high levels of feedback torque, the steering wheel became unstable and began to oscillate near the center point. Since motor control was not possible using the existing steering model and controller, steps were taken to control the motor using external hardware and software.

The motor was controlled by an Arduino Duemilanove microcontroller and motor driver. The motor driver used was a Pololu High-Power Motor Driver 18V15A, a discrete MOFSET H-
bridge motor driver. The motor driver’s 1.3x0.8 inch board supports a wide 5.5 V to 30 V range and is efficient enough to deliver a continuous 15A without a heat sink. The specifications of the Pololu motor driver were suitable for bidirectional PWM control of the DC brushed motor used in the simulator. Control over the PWM of the motor resulted in control over the reactive torque produced.

3.2.4 User Interface to Control Steering Effort
A push button interface was built onto the steering wheel to enable drivers to control steering effort manually while driving the vehicle. Two push buttons as shown in Figure 3.2 were designed on the steering wheel. While one of the buttons was used to increase steering effort, the other was used to reduce steering effort. The effect of the buttons was programmed with the Arduino Duemilanove microcontroller, which also determined the step size for increase and decrease of steering effort. A step size of 20 PWM (20% differences in pulse width modulations) was chosen as it was found to produce noticeable variations in steering effort from pilot studies. The interface was programmed to provide six different levels of steering effort to drivers. To keep participants informed about the currently selected level, an 11” LCD display was used. The display was positioned similar to an in-car navigation device and interfaced with the Arduino using Sketchify, a prototyping design program developed by Eindhoven University of Technology (Obrenovic and Martens, 2011), to display the steering effort level. Levels were displayed to participants as text labels such as Level 1, Level 2 ... Level 6.

3.2.5 Steering Effort Measures
The actual values of steering effort for each of the programmed levels were measured using a digital force gauge with standard error of +/- 0.1 N. Measurements were transformed into torque values by multiplying measured force for each level with the distance between the center of steering wheel and the actual position of force measure. The torque values, the reactive torque, measured for each of the levels offered to participants are as shown in Table 3.1. The torque measures are produced by varying the PWM values of the motor in step sizes of 20 as mentioned above. The torque was applied as a constant torque when the steering wheel was moved away from the center. Subjects were thus able to experience the maximum torque of a particular level instantly when moving away from the center to turn or overtake.
Table 3.1. Measures of reactive torque across six levels of steering effort.

<table>
<thead>
<tr>
<th>Steering Effort Level</th>
<th>Measured Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>0.84</td>
</tr>
<tr>
<td>Level 2</td>
<td>2.24</td>
</tr>
<tr>
<td>Level 3</td>
<td>2.95</td>
</tr>
<tr>
<td>Level 4</td>
<td>3.85</td>
</tr>
<tr>
<td>Level 5</td>
<td>5.78</td>
</tr>
<tr>
<td>Level 6</td>
<td>6.90</td>
</tr>
</tbody>
</table>

3.2.6 Experimental Task

The experimental tasks required participants to drive through four scenarios and execute the necessary steering maneuvers to maintain lane position and control of the vehicle. For the experimental study, four driving scenarios were selected: 1) Parking_Reverse 2) City 3)
Subjects drove a simulated Audi A4 vehicle during the experiment. In the Parking_Reverse scenario participants were required to perform parallel, forward and reverse parking assignments in designated parking bays in the circuit.

The City and Countryside driving environment required participants to navigate through sharp curves, gradual curves and straight lanes. Since some participants in a pilot study reported preferences for the settings in each of the three driving segments separately in these two scenarios, participants were asked to report their preferences separately for each segment in the scenarios as well. In the City scenario, the road was two-lane with center-line road markings, pedestrian lanes and footpaths. The traffic in the City scenario consisted of four wheeled passenger cars, scooters, bi-cyclists and pedestrians which is similar to a Dutch city environment. Drivers were free to choose their own route in the City scenario. In the Countryside scenario, the road was two-lane with center line markings and did not have both bicycle lanes and footpaths for pedestrians. In this scenario, passengers encountered only four-wheeled passenger vehicle traffic. The Highway driving environment required participants to navigate through straight lanes and few gradual curves in a two-lane road separated by a center median. Emergency shoulder lanes and road rumblers beyond the lane markings ensured that participants received audio reinforcement to get back in the driving lane. Moderate four-wheeled traffic travelling at high speeds was simulated in the Highway scenario. Images of the circuits for the scenarios are shown in Figure 3.3. Participants in the City, Countryside and Highway scenarios were instructed to not exceed speeds of 50 kmph, 80 kmph and 120 kmph respectively to comply with Dutch road rules. In addition to instructions, participants also encountered speed posts in the scenario indicating speed limits.

The City, Countryside and Highway scenarios included moderate traffic to increase realism of the simulation. A screenshot of traffic in the Highway scenario can be seen in Figure 3.4.
3.2.7 Procedure

The experiment was conducted in the simulator laboratory at Eindhoven University of Technology. Once informed consent was obtained from participants and their driving license verified, the pre-task questionnaire was administered. On completion of the pre-task questionnaire, participants were asked to seat themselves in the driving simulator as they
would in a real car. To familiarize participants with the experimental setup and driving in the simulator, a familiarization trial was conducted. In the familiarization run participants were provided instructions as to how they could experience the entire range of forces which the steering wheel would transmit as reactive torque. They were then allowed to increase and decrease reactive torque using the buttons to navigate across force levels. They were also allowed to drive on a highway scenario with no traffic for 2 minutes as part of the familiarization run.

Participants were then given instructions on performing the experimental task. All participants received the same instructions orally from the experimenter. The instructions specified that they would receive four different scenarios in which they were to drive as they would on real roads following basic road rules and speed limits. Participants were also instructed to navigate across all 6 levels of feedback torque while driving and state their subjective opinion of each level in general terms. This was done to elicit spontaneous subject response to a force level and identify specific terms used to describe differences between levels. Participants always began driving at Level 1 (the default start setting of the Arduino code) and we asked to experience different levels of steering effort by pressing the increase and decrease buttons on the steering wheel. Finally participants were asked to indicate their preference for a particular steering effort level that they would like to drive on in a real car. Instructions were repeated prior to each of the 4 scenarios. Pilot studies suggested that Parking_Reverse could result in simulator sickness due to the nature of the steering maneuver (frequent movements) and movement of the head in combination with change in graphics. The order of scenarios (Countryside -> City -> Highway -> Parking_Reverse) was chosen to reduce simulator sickness and to enable participants to complete the experiments. Therefore the Parking_Reverse scenario was provided at the end preceded by the Highway scenario, which in a pilot study was suggested to be most easy and comfortable. The order of the first two scenarios, City and Countryside, was selected at random. At the end of the experiment, participants were administered the post-task questionnaire to complete their participation.

3.2.8 Participants
Participant recruitment followed convenience sampling. 26 participants, comprising mostly of students and researchers associated with Eindhoven University of Technology, were recruited for the study. Gender balance was maintained in participant recruitment to study gender effects on preferred steering effort. Therefore, 13 males and 13 females were recruited for the study. All participants had a minimum driving experience of 1.5 years and drove a car on a regular basis. Participants in the study had a mean age of 25 years and 10 months (26 years and 3 months for males, 25 years and 6 months for females), ranging from
19 to 45 years and a driving experience of 5.5 years (6.0 for Males, 4.9 for Females), ranging from 2 to 12 years.

3.3 RESULTS AND DISCUSSION
Means were computed across subjects separately for male and female participants. For the City and Countryside scenarios, a distinction was made between Sharp Curves (SC), Gradual Curves (GC) and Straights (S), as average speed is different for these situations and it is well known that steering effort varies with speed. The resultant plot is shown in Figure 3.5.

Looking at the graph in Figure 3.5, it can be seen mean preferences for steering effort were closer together at medium speeds (Countryside) compared to high speeds (Highway). Figure 3.5 also shows that preferred force increases with speed. Interestingly at medium speeds, it appeared that females prefer slightly (but not significantly) higher steering effort when compared to males. This differs from findings of earlier studies that have shown that males prefer higher steering effort across various conditions. In the study conducted by Barthenheier and Winner (2003), males preferred higher steering effort when driving fun was the criterion. In the current study, no such criterion for preferences was set. The findings therefore represent a more natural selection for preferred steering effort.

Figure 3.5. Means ±1 standard error for preferred steering effort setting for males and females in different driving conditions. The x-axis represents the Parking_Reverse (Park/Rev), City Sharp Curves (City SC), City Gradual Curves (City GC), City Straights, Countryside Sharp Curves (CS_SC), Countryside Gradual Curves (CS_GC), Countryside Straights (CS_S) and Highway conditions.
A Shapiro-Wilk test was conducted on the preference data and results revealed a non-normal distribution and hence non-parametric tests were adopted for subsequent analyses. Friedman’s Analysis of Variance (ANOVA) was first conducted to look for significant differences among the three conditions within the City and Countryside scenarios, respectively. Results revealed that the preferences for these conditions did not vary significantly for either the City ($\chi^2 (2) = 2.92, p = .23$) or Countryside ($\chi^2 (2) = 3.12, p = .65$) scenarios. The three conditions for each of the scenarios were then collapsed to calculate means for each participant across the three conditions to represent preferred steering effort levels for City and Countryside scenarios. The mean scores were then used for subsequent data analyses.

The scores for preferred steering effort were analysed to look for the effect of gender in preferences for steering effort across scenarios by performing a Kruskal-Wallis test. Results showed that the effect of gender was not significant ($\chi^2 (1) = .53, p = .46$).

A Friedman’s ANOVA was then performed to see whether the preferences for steering effort varied based on scenarios across participants. Results showed that the effect of scenarios was significant ($\chi^2 (3) = 38.06, p = .00$). Wilcoxon Signed Ranks tests were then performed as post-hoc analyses to compare preferences in the scenarios pairwise. Results are shown in Table 3.2. The critical significance level for the pairwise comparisons applying Bonferroni corrections was set at $p = .008$.

The results from the pairwise comparisons indicate that there are significant differences in preference for steering effort between scenarios except for the City and Countryside scenario comparison ($p > .008$), suggesting preferences are similar between these two scenarios based on adjusted level of significance.

Looking at the graph in Figure 3.5, it can be seen that mean preferences for steering effort were closer together at medium speeds (Countryside) compared to high speeds (Highway). Figure 3.5 also shows that preferred force increases with speed. Interestingly, at medium speeds, it appeared that females prefer slightly (but not significantly) higher steering effort when compared to males. This differs from findings of earlier studies that have shown that males prefer higher steering effort across various conditions. In the study conducted by Barthenheier and Winner (2003), males preferred higher steering effort when driving fun was the criterion. In the current study, no such criterion for preferences was set. The findings therefore represent a more natural selection for preferred steering effort.
Table 3.2. Results from Wilcoxon Signed Ranks Test.

<table>
<thead>
<tr>
<th></th>
<th>Parking_Reverse</th>
<th>City</th>
<th>Countryside</th>
<th>Highway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parking_Reverse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City</td>
<td>( Z = 2.87, \ p = .004 )</td>
<td>( Z = 3.59, \ p = .000 )</td>
<td></td>
<td>( Z = 4.02, \ p = .000 )</td>
</tr>
<tr>
<td>Countryside</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( Z = 2.93, \ p = .003 )</td>
</tr>
</tbody>
</table>

While the effect of Gender was not significant, closer inspection of the data for individual participants as shown in Table 3.3 indicated that there were differences in preferred levels of steering effort between individual participants. Participants are ordered with respect to the preferred level for Parking (in increasing order), next with respect to the preferred ordered for City and so forth.

Two facts may be noted about this table. In the first place, there is a more or less orderly progression from Parking_Reverse to \{City, Countryside\} to Highway, such that for most participants the preferred level of steering effort for City and Countryside was higher than for Parking, and that the preferred level of steering effort was higher for Highway than for City and Countryside, in conformity with the trend shown in Figure 3.5. This progression is statistically significant, as shown by the outcomes of pair-wise comparisons by means of Wilcoxon’s Signed Ranks test.
Table 3.3. Mean preferred steering effort (in Nm) for individual participants in Parking Reverse, City driving, Countryside driving and Highway driving.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Parking Reverse</th>
<th>City</th>
<th>Countryside</th>
<th>Highway</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>0.84</td>
<td>0.84</td>
<td>0.84</td>
<td>2.95</td>
</tr>
<tr>
<td>M</td>
<td>0.84</td>
<td>2.24</td>
<td>5.58</td>
<td>6.90</td>
</tr>
<tr>
<td>F</td>
<td>0.84</td>
<td>2.78</td>
<td>3.25</td>
<td>5.78</td>
</tr>
<tr>
<td>M</td>
<td>0.84</td>
<td>3.85</td>
<td>3.85</td>
<td>0.84</td>
</tr>
<tr>
<td>M</td>
<td>2.24</td>
<td>2.24</td>
<td>2.24</td>
<td>3.85</td>
</tr>
<tr>
<td>F</td>
<td>2.24</td>
<td>2.71</td>
<td>3.85</td>
<td>2.95</td>
</tr>
<tr>
<td>F</td>
<td>2.24</td>
<td>2.95</td>
<td>2.95</td>
<td>2.24</td>
</tr>
<tr>
<td>M</td>
<td>2.24</td>
<td>2.95</td>
<td>2.95</td>
<td>2.95</td>
</tr>
<tr>
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<tr>
<td>M</td>
<td>5.78</td>
<td>3.25</td>
<td>5.78</td>
<td>6.90</td>
</tr>
</tbody>
</table>

A box-plot (as shown in Figure 3.6) of the preferred steering effort constructed for each scenario shows the overall trend of preferences across individual subjects. Red lines within the blue boxes indicate mean values. The plot indicates that steering effort should increase with speed, mimicking the well established connection between feedback torque and speed in
conventional systems (as seen in Figure 2.5) while also showing that there are individuals who do not prefer such settings as can be evidenced by the outliers (indicated by +). Secondly, the increase in preference range for the Highway scenario above the mean suggests that variation in preference for the Highway scenario is higher in comparison with the other three scenarios.

The second fact to be noted from Table 3.3 is that, for the majority of participants (80% or more), preferences for steering effort in the Parking_Reverse conditions are between 2 and 3 Nm, for City and Countryside between 2 and 4 Nm, and for Highway between 2 and 7 Nm. Thus, while a fixed setting of steering effort between 2 and 3 Nm appears to be acceptable for the majority of drivers in the case of Parking_Reverse, for the other scenarios there is a much larger variation, so that a fixed setting, for instance between 2 and 3 Nm, would not do justice to the preferences of the participants.

The observation shows that drivers would be more suited with a system that allows them to adjust the steering effort. However, a question for further investigation is to explore how drivers would like these settings to be adjusted or whether the system should make changes on its own taking into account driver preferences.

In order to explore whether these preferences for lower or higher reactive torque were related to individual characteristics, we inspected relations between the chosen levels of steering effort and the ratings for the relative importance for comfort and control in the pre-test questionnaire (5 point scales with 5 = high importance). This was motivated by statements such as “Level 6 gives more control but it will be exhausting for a long drive” and “Level 3 is comfortable, but Level 4 gives more control” by participants while thinking aloud.

**Figure 3.6. Box-plots for preferred steering effort across the four driving scenarios.**

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during the driving task. The reasoning was that drivers prioritizing comfort might select a relatively lower steering effort, and those drivers prioritizing control might have a preference for a more direct steering feel, resulting in a preference for more steering effort. However, the questionnaire data indicated that all drivers attached high importance both to comfort (mean importance = 4.27) and control (mean importance = 4.77). Given the small dispersion both for comfort and control, it may already be expected that correlations between subjective importance for control and comfort, respectively, will be low, and this was confirmed. Pearson correlations between overall mean preferred steering effort for individual participants and the scores for Comfort and Control were 0.03 and 0.02, respectively.

3.4 CONCLUSION AND GENERAL DISCUSSION
The study aimed to determine how preferences for steering effort varied based on gender and across various driving scenarios with a self-controllable user interface on the steering wheel. While preferences were found to vary between driving scenarios and individuals, the study failed to confirm that gender significantly impacted preferences as reported in earlier studies.

Unlike Green et al., (1984) and Barthenheier and Winner (2003), the current study did not find an effect of gender on preferred steering effort. The sample size used could have contributed to lack of significant differences as each gender group had a size of only 13 participants while Barthenheier’s study (2003) had approximately 200 participants. The study also did not recruit populations with diversity in age, and so the effect of age was not studied.

Participants also offered mixed reactions to the push button user-interface provided on the steering wheel (the primary HMI). While there were participants who stated that the presence of an adjustable user interface would be more “flexible” and “comfortable”, there were those who stated that their preference for steering effort be programmed and automatically offered by the system while driving. Some participants were also skeptical of the additional workload that a manually adjustable user interface may impose on the driver and did not feel confident to make an assessment of the usability of such an interface in a real driving environment. There were also participants who stated their preference for an interface that offered few discrete levels of steering effort which were adaptive to speed. The findings bring about the need to conduct further research in the design of such user interfaces to gather requirements. It must be reminded that the interface used in the study was basic with the objective of studying preference rather than HMI design.

In conclusion, the present study gives the following main outcomes. In steer-by-wire systems, drivers prefer reactive torque to mimic the dependency on speed found in
conventional steering systems, such that steering effort should remain a function of driving speed. In addition, we find that there are individual differences with respect to preferred levels of steering effort, such that some drivers prefer lower levels of steering effort and other drivers prefer higher levels of steering effort depending on the driving scenario. However, these individual differences are not related to gender or to individual differences in priorities for control or comfort, both of which appear to influence preferences for steering effort.

In the next study presented in Chapter 5 we will investigate a potential trade-off between comfort and control, and address the question of how steering effort is related to perceived comfort and control. So far the driver characteristics that affect preferences remain unexplained. Therefore studies that instead focus on driving performance, driver behavior in relation to variation in steering effort and other steering feel parameters will be conducted to gather user requirements and make further recommendations for the design of steer-by-wire systems and also user interfaces that enable personalization of steering.

In setting up the driving simulator for this study, several limitations that could affect further research on SbW systems were identified. It was found that the driving simulator set up differed significantly from the prototype SbW car which had a flexible steering model that offered enhanced control over the steering actuator. Hence, certain upgrades had to be made for future research. These upgrades are presented in detail in the next chapter.
CHAPTER 4

Driving Simulator Upgrades
The previous study highlighted that the fixed-platform driving simulator manufactured by Green Dino B.V provides flexibility in creating different driving environments and also manipulating elements in the environment such as traffic behavior. The study revealed to us that there were hardware limitations with the original set-up of the steering system in the simulator and these had to be overcome in enhancing operational capabilities of the simulator for SbW research. This chapter presents a more detailed description of the driving simulator and hardware upgrades that were performed.

4.1 Simulator Overview

The driving simulator was manufactured by Green Dino B.V in The Netherlands. In their own words, “the company is a manufacturer of driving simulator with automated monitoring, evaluation and instruction for competence-oriented training” (from www.greendino.nl). The focus of Green Dino has been on creating virtual environments simulating on-road driving in aspects relevant to the training of driving skills. In recent years, they have increased collaboration with universities of technology such as Eindhoven University of Technology to offer research support.

The software application for the driving simulator offers customizable lessons in which the scenario design, 3D environments, traffic behavior and vehicle characteristics can be modified. The driving simulation software is built to simulate a range of driving tasks and this makes it suitable for Human Machine Interaction research where driver behavior can be studied while engaged in specific tasks. A range of driving parameters can be observed, stored and analyzed. The data from the simulator can also be deployed in real-time through third party software such as Matlab and Simulink, making it possible to enable and modify cruise control data and integrate warning devices (Shahab, 2014). The driving simulator allows the selection of different vehicle models, including a mid-size passenger car and a heavy-duty truck. Changing the vehicle model also results in a corresponding change to the steering characteristics. The dynamics on which the vehicle models are based can be found in Beckman (1991). Simulator studies presented in this thesis used the passenger car vehicle model.

4.2 Steering Control

The actuator providing the steering feedback was a brushed DC motor that was coupled to the steering wheel via a steering rack. The motor was fitted with a step-up device to offer up to 7 Nm of feedback torque. The feedback was controlled by an internal algorithm which calculated input voltage to the motor as a function of vehicle speed, steering wheel angle and rate of steering. The input voltage was then sent to the feedback motor to deliver required torque. The system therefore resembled a Variable Power-Assist (VPA) system.
The maximum forces generated through the algorithm were no greater than 1.5 Nm of force, which is considerably lower than feedback torque experienced in passenger cars and also below the peak torque capability of the motor itself. Limitations were also observed in manipulating the steering algorithm. The feedback algorithm contained several parameters internally defined by Green Dino to suit the hardware and these values could not be directly mapped with parameters observed in a conventional steering model. Furthermore, the parameters could not be modified in real-time to easily study the effect of changes in parameter values. An application for monitoring the motor characteristics was also absent and this meant that feedback torque changes had to be measured and verified manually using devices such as force gauges. These manual techniques are susceptible to error. There were also limitations in controlling the feedback externally as it had to be done via the motor controller which did not have a software application. Input voltages to the motor controller therefore had to be supplied manually through an external power source. The electrical box in which the motor controller was housed, was affected by electrical disturbances and produced undesired jitters on the steering wheel. While the electrical disturbance issue was overcome by filtering signals, there was significant lack of flexibility in modifying the steering feedback with the existing steering actuator mechanism.

In the previous study, external control of the motor was gained by using an external motor controller. The motor controller used was a Pololu High-Power Motor Driver that was able to control output of the motor by varying the Pulse Width Modulation (100%) of the motor and also had directional control to ensure feedback was offered against the direction of turn. The Pololu motor driver had to be controlled through an Arduino microcontroller which offered the PWM input. As is evident, these were short-term prototyping solutions that specifically catered to creating symmetrical torque to test preference for feedback torque on the steering wheel. In addition to the above mentioned issues, precise control over the motor was also not possible as it was a brushed-type motor. It is known that brushed-type motors offer less control in comparison to other type of motors.

4.3 Need for a Steering Model

The driving simulator with its existing operational capabilities did not resemble SbW systems which offer increased functionality and advanced control over steering feedback. To conduct research studies for such advanced systems, a simulator must be capable of offering researchers high level of flexibility and accuracy in adjusting steering settings. As mentioned in Chapter 2, in SbW systems, a steering model is required to control the working of a steering system. The simulator therefore needs a steering model with controllable parameters as seen in state-of-the-art and suitable hardware that is well defined in terms of its control for conducting research with steering settings. And for SbW the model must be capable of being modified in real-time. Such upgrades were needed for maintaining precise
control over the motor for feedback torque studies and also to study and map changes in steering parameters to subjective experience attributes.

4.4 Hardware Upgrades

The brushed-type motor and gear rack assembly were replaced with a brushless AC motor which was directly coupled to the steering wheel. The motor was manufactured by ACM engineering S.P.A in The Netherlands (motor specifications are attached in Appendix A.1). The motor is controlled by an advanced motor controller Mini OPD EXP, manufactured by TDE MACNO (specifications in Appendix A.2).

The new motor and its controller are a much more robust and flexible alternative to the original set-up. The controller can also be placed outside the simulator control box to overcome electrical disturbances. The motor controller comes with a software package (OPD explorer desktop application) that allow to control a number of steering parameters such as output torque, return-to-center speed, stiffness and damping coefficient. The motor controller can be programmed to operate in modes such as symmetrical torque control, speed control and pure torque control. The performance of the motor can be observed in real-time using the OPD explorer application to ensure that the operational characteristics match requirements. With the new motor, it is possible to define the feedback torque more accurately. The motor was initially operated in symmetrical torque (constant torque) mode to study factors influencing preferences and also the driving performance with particular level of feedback torque. The feedback torque was controlled using a potentiometer which regulated input voltage to the motor. The input to the motor can be varied between 0 and 10 volts to vary the output torque. The potentiometer, which acts as voltage divisor, has ten presets; each of them providing increments of 1 volt. The relationship between the input voltage and output torque is defined in Equation (4.1). With this configuration it is possible to set different torque levels by manually varying the potentiometer.

\[ T_n = 0.8 \left(V_{input}\right) \text{[Nm]} \] (4.1)

4.5 Steering Model Upgrades

While the symmetrical torque set-up is useful to study the effects of different feedback torque levels, the simulator must also be capable of simulating feedback as a function of steering angle and speed as done with real cars. There must be a steering model implemented to control steering feedback and the operation must be flexible such that parameters of the model can be modified to facilitate different steering feedback profiles. Chapter 1 discussed that one of the goals of the research is to explore the subjective space and map subjective parameters to physical steering parameters. In order to do that, a steering model had to be integrated with the driving simulator.
The steering wheel model that was integrated in the simulator was developed as part of a master thesis (Okutman, 2011) at Eindhoven University of Technology (TU/e). The model is accurate to provide realistic steering feedback and can also be easily modified in real-time. The steering feedback was modeled as a combination of the following:

- The feedback moment measured from the steering axes i.e., the forces on the steering rack. This represents the transmission of road-tyre contact forces to the steering wheel via the steering system.
- The stiffness, which is modeled as a spring for the steering wheel. It creates the return-to-center feeling, which aids in perception of center point.
- The contribution of the dry and viscous friction, i.e. the damping. The damping helps create a more robust control of the steering wheel.
- The steering column inertia is also introduced.

The original values of the vehicle parameters, which belonged to a BMW 5231 were modified to match that of the driving simulator vehicle model, which corresponds to an Audi A4. The modifications to the model and further development for integration with the simulator were performed by Juan-Carlos Sanchez, who was a master student at TU/e. Sanchez also developed and integrated variable power assist and variable gear ratio functionality into the steering model (Sanchez, 2012).

4.6 Simulator Status

Hardware and software upgrades were made to the driving simulator to enhance its operational capabilities and flexibility to support SbW research. Hardware upgrades were carried out in 2011 and provided increased instrumental control over symmetrical torque feedback. Software upgrades which commenced towards the third quarter of 2011 were completed in the first quarter of 2012. Software upgrades included integration and development of an existing steering model proven to offer feedback as done in real cars. Developmental work performed by Sanchez (2012) ensured that different parameters of the model could be varied in real-time to test different types of steering settings. Elements of steering feel other than force could now be studied in the simulator. The steering model was also flexible enough to tests ADAS systems.
CHAPTER 5

Impact of Feedback Torque Level on Perceived Comfort and Control & Driving Performance

This chapter is based on:


5.1 INTRODUCTION

The study reported in Chapter 3 indicated that drivers evaluate a given level of feedback torque based on their perception of comfort and control. While comfort and control are commonly used terms, their definition in the context of steering wheel feedback torque is not entirely clear. While reduction in force by increasing power assistance is commonly associated with increasing comfort (Chabaan & Wang, 2001; Klier, Reimann & Reinelt, 2004), studies do not offer in depth analysis of the relationship between feedback torque and comfort. Similarly, for control there has been a focus on controller designs (Mammar & Koenig, 2002) for control improvement but not much study happened on the relationship between magnitude of feedback torque and control. Anecdotal evidence from web forums discussing steering, indicates that this relationship is subjective and based on an individual’s preference of feedback torque for comfort and control. With only a high level understanding of the relationship between comfort, control and feedback torque, the task of designing steering systems offering optimal levels of comfort and control is difficult. Furthermore, it is unclear if individual preferences for a particular feedback torque level are made by striking a compromise between comfort and control. The aim of the experiment is therefore to study in detail the impact of feedback torque level on perceived comfort and control.

As mentioned above, literature states that comfort decreases more or less linearly with increasing feedback torque (Newberry et al., 2007). However, we assume that there will be a secondary effect at very low to zero levels of torque, where comfort is assumed to be low because of complete lack of normal steering wheel characteristics such as return-to-center. On the other hand, we assume that control increases more or less linearly with increasing torque, except for a similar secondary effect at very high levels, where the feedback torque is so high that it is difficult to execute the intended steering maneuver. The hypothesized relationships between feedback torque levels and comfort and control as shown in Figure 5.1 imply that optimal torque levels for comfort and control may be different. If so, drivers need to find a compromise between comfort and control, and furthermore it may be expected that the compromise will not be the same for all drivers.
To test this hypothesized relationship a study was conducted. With lack of clear understanding of comfort and control in the context of steering, the study also explores the underlying attributes that define comfort and control and the relationship between the two when feedback torque is varied. Additionally, the chapter also studies the relationship between subjective experience and objective driving performance, by investigating driving performance as a function of feedback torque. Investigation will show whether feedback torque levels that are perceived to offer better comfort and control improve driving performance and vice versa.

5.2. METHOD

5.2.1 Experimental Design

The experiment followed a mixed method within-between subjects design. Six levels of feedback torque ranging from 0 Nm to 7.2 Nm were applied to a steering wheel in the fixed-base Green Dino driving simulator to allow participants to experience a wide range of forces that included feedback forces normally encountered in a vehicle as well as extremely low and high forces. Since the primary objective of the study was to explore the attributes that relate to comfort and control in the context of steering, the experimental setup was designed such that participants’ judgments of comfort and control across the six different force levels were recorded quantitatively by means of a questionnaire.

Comparing all six different levels of feedback torque only after drivers have experienced all six levels causes methodological problems; judgments are likely to be heavily influenced by the order in which the levels were offered. As the time required to experience a particular feedback torque level is substantial (in the order of minutes), this would imply a large time interval between experiencing the first feedback torque level and making the judgment. It is known that such reliance on memory may favor more recent (Mayo and Crockett, 1964) and...
more extreme experiences. Pairwise comparison is known to be a more stable experimental method and has therefore been adopted instead. This implies that participants perform the driving task with two different torque levels and subsequently make a comparison between the two on a questionnaire. With six different torque levels, a comparison matrix yields 30 ordered pairs. Each participant was offered only three pairs, selected at random, in order to prevent participant fatigue. A minimum of 10 participants is therefore required to make all 30 (10 x 3) pairwise comparisons.

5.2.2 Participants

Thirty (N = 30) participants who were regular drivers of a passenger car with a minimum of 1.5 years of driving experience were recruited to take part in the study. Participants recruited consisted mostly of students affiliated with Eindhoven University of Technology. Of the 30 subjects, 27 were male and 3 were female. Since the earlier study (Anand et al., 2011) conducted on the simulator revealed that the effect of gender on preferred steering force was insignificant, participant recruitment did not require gender equality. Of the 30 subjects, 10 had driving experience ranging between 1.5 and 3 years, 7 had between 3 and 5 years of experience, 10 had between 5 and 10 years and 3 had over 10 years of driving experience. 10 subjects had annual driving mileage of less than 5,000 km, 11 subjects between 5,000 and 10,000 km, 6 subjects between 10,000 and 20,000 km and 1 subject greater than 20,000 km.

5.2.3 Questionnaire

A post-task questionnaire (as in Appendix B.1) to make the pairwise comparisons was developed for the study. Items included in the questionnaire were outcomes of a pilot study. In the pilot study, six doctoral students from Eindhoven University of Technology were recruited using convenience sampling to perform the same driving task as in the experiments but were asked to compare forces in triads instead of pairs. Comparisons were expressed verbally via interview. The interviewing style followed the repertory grid technique (Fransella, Bell & Bannister, 2004) and used laddering up and down. Interviews focused on gaining an understanding of how participants make comparisons with regard to steering wheel feedback torque and also specifically into what comfort and control meant to subjects and the description of these terms in their own words. Content analysis of the interviews provided common terms that participants used in characterizing the experienced forces. Items that provided a general characterization of force and items that were relevant to comfort and control were first included in the questionnaire, to a total of twenty items. Seven items were included later on based on feedback from the first ten participants. Of the seven additional items, four provide subjective assessment of comfort and control when driving in straights and corners while the remaining three focus on attention, mental effort
and physical effort required in performing the driving task. The initial 20 and additional 7 items are listed in Table 5.1.

For each item, the post-task questionnaire contained a binary response question and a 5-point Likert type scale. The binary response question was to elicit whether the perceived effect of the attribute was “More” or “Less” when comparing the second force level in a pair with the first. The 5-point Likert-type scale below the binary response question allowed participants to indicate how much more or less the difference was between the two force levels for a particular attribute.

**Table 5.1. Questionnaire Items**

<table>
<thead>
<tr>
<th>Initial 20 Items</th>
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<table>
<thead>
<tr>
<th>Additional 7 Items</th>
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</thead>
<tbody>
<tr>
<td>22. Turn Control</td>
</tr>
</tbody>
</table>

### 5.2.4 Equipment

The driving tasks were performed in the fixed-base Green Dino Driving simulator. Participants drove a simulated vehicle which had parameters of an Audi A4 vehicle. The feedback force was varied from 0 % - 90 % of the rated motor torque of 8 Nm. The variation in percentage of rated torque between levels from Level 2 up to Level 6 was designed such that torque varied beyond the just noticeable difference (JND) value of 17 % (Newberry et al., 2007). In terms of the design of feedback torque, the magnitude of force was kept constant and was intentionally not varied in response to speed and steering angle, in order to present all participants with a uniform force sensation in each level. This form of constant symmetrical feedback torque differs from the way in which force feedback is experienced in
a conventional steering system. The on-center feel was not uniform as the different levels of torque created varying levels of boundaries for on-center i.e., the steering felt more rigid and stiff with increasing levels of torque even during on-center handling. The force feedback applied in each of six levels is as shown below in Table 5.2.

Table 5.2. Six feedback torque levels offered to participants.

<table>
<thead>
<tr>
<th>Feedback Torque Level</th>
<th>Percentage of Rated Torque (8Nm) in %</th>
<th>Actual Torque Produced (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Level2</td>
<td>10</td>
<td>0.80</td>
</tr>
<tr>
<td>Level3</td>
<td>30</td>
<td>2.40</td>
</tr>
<tr>
<td>Level4</td>
<td>50</td>
<td>4.0</td>
</tr>
<tr>
<td>Level5</td>
<td>70</td>
<td>5.60</td>
</tr>
<tr>
<td>Level6</td>
<td>90</td>
<td>7.20</td>
</tr>
</tbody>
</table>

5.2.5 Driving Task

The experimental task required participants to navigate a 3.6 km circuit shown in Figure 5.2. Segment details of the corners are shown in Table 5.3. The circuit required participants to begin driving from the ‘Start’ position and execute 11 corners before coming to a stop. The circuit had low density traffic in the opposite lane to simulate a realistic countryside driving environment and prevent intentional lane departures. Participants were instructed to keep to the center of the lane while driving through the circuit. Participants were given control over their driving speed but were instructed to drive at speeds at which they would drive in a similar scenario on actual roads.
5.2.6 Procedure

Upon obtaining informed consent, demographic information such as gender and driving experience was collected from participants. Then they did a familiarization trial to get familiar with the experimental set-up. Familiarization involved participants driving on the driving circuit for approximately five minutes with a mid range level of feedback torque.
Following familiarization, participants were instructed to perform the driving task twice, each time with a different torque level. On completion of the driving task, participants were instructed to complete the post-task questionnaire and make pairwise comparison of the settings on attributes relating to comfort and control as listed in Table 5.1.

Upon completing the questionnaire, each participant performed the driving task with two other pairs of feedback torque levels and made comparisons on the post-task questionnaire as previously instructed. In total, each participant received 3 pairs of feedback torque and expressed pairwise judgments for the different items offered in the questionnaire. The duration of the experiment was approximately 60 minutes per participant. The driving simulator logged several parameters which included lane position, longitudinal velocity and steering wheel angle. Data were logged at a rate of 20 Hz. Standard performance metrics such as Standard Deviation of Lane Position (SDLP) and Standard Deviation of Steering Wheel Angle (SDST) were calculated as deviations from the mean of the sample values for each individual run.

5.3 QUESTIONNAIRE RESULTS AND DISCUSSION

5.3.1 Results

Cluster analysis was performed, using a developer’s version of Ilmo (Martens, 2012), a statistical package, across all participants on the pairwise comparison data which comprised of average scores for 20 attributes from all 30 participants and for 7 attributes from 20 participants. The analysis was therefore performed with missing data for the 7 attributes that were not included in the post-task questionnaire offered to the first 10 participants in the study. Clusters that could not be described as one-dimensional (established by the size of the second singular value) were iteratively split into smaller clusters, but clusters that would only be supported by a single attribute were avoided. Whenever a cluster was split, all attributes were iteratively assigned to the cluster with which they had the highest correlation. The analysis revealed that attributes could be grouped into four clusters. The clusters formed can be seen in Table 5.4.
Table 5.4. Four clusters formed from preference scores on clustering analysis with explained variance values for each item.

<table>
<thead>
<tr>
<th>Cluster1</th>
<th>$R^2$</th>
<th>Cluster2</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trustworthy</td>
<td>0.34</td>
<td>Tiring</td>
<td>0.83</td>
</tr>
<tr>
<td>Secure</td>
<td>0.53</td>
<td>Physical Effort</td>
<td>0.87</td>
</tr>
<tr>
<td>Safe</td>
<td>0.53</td>
<td>Heavy</td>
<td>0.93</td>
</tr>
<tr>
<td>Control</td>
<td>0.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exaggerated From Normal</td>
<td>0.70</td>
<td>Cluster3</td>
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</tr>
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<td>0.73</td>
<td>Natural</td>
<td>0.65</td>
</tr>
<tr>
<td>Mental Effort</td>
<td>0.75</td>
<td>Straight Comfort</td>
<td>0.79</td>
</tr>
<tr>
<td>Doable</td>
<td>0.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Requires Attention</td>
<td>0.81</td>
<td>Cluster4</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Frustration</td>
<td>0.86</td>
<td>Sturdy</td>
<td>0.04</td>
</tr>
<tr>
<td>Pleasurable</td>
<td>0.87</td>
<td>Turn Control</td>
<td>0.42</td>
</tr>
<tr>
<td>Comfort</td>
<td>0.88</td>
<td>Turn Comfort</td>
<td>0.79</td>
</tr>
</tbody>
</table>

On observation of the individual attributes within the clusters, the clusters were assigned the following semantic terms: Cluster 1 = Overall Comfort & Control, Cluster 2 = Physical Effort, Cluster 3 = Straight Comfort & Control and Cluster 4 = Turn Comfort & Control.

As can be seen from the Overall Comfort & Control cluster, comfort and control are not perceived distinctly by subjects. The high correlations between Comfort and Control rating scores across participants ($r = 0.9$, $p < .001$) reinforce this impression. The results further reveal other items which are related to Comfort and Control. The results therefore reject the initial hypothesis that comfort and control are perceived distinctly.
In order to understand the relationship between the clusters and the force levels, the preference scores of individual attributes were analyzed using multi-dimensional scaling (MDS) software. Since a two-dimensional solution did not explain more variance, a one dimensional solution was used. The analyses treated participants as a homogenous group, although there were some outliers in terms of their judgment of forces. Results from the analysis produced the patterns shown in Figures 5.4a – 5.4d as a function of force level for the different clusters. The black squares indicate mean values while the whiskers represent the 95% confidence intervals. With exception of Cluster 2, Physical Effort, the relationships are non-linear as a function of force level.

Figure 5.4a.
Cluster 2: Physical Effort

Subjective Ratings vs. Feedback Torque (in Nm)

Cluster 3: Straight Comfort & Control

Subjective Ratings vs. Feedback Torque (in Nm)

Figure 5.4b.

Figure 5.4c.
5.3.2 Discussion

The non-linear relationships for Clusters 1, 3 and 4 produce a similar pattern as observed in Figure 5.1, where it was assumed that a secondary effect may modulate the linear relation between feedback torque level and the perceived psychological construct. The patterns confirm the existence of a secondary effect which influences perceived comfort and control, indicating that too high and too low force result in less perceived comfort and control.

The pattern in Figure 5.4a illustrates that maximum comfort and control are perceived at 0.8 Nm and 2.4 Nm followed by 0 Nm and 4 Nm. The least comfort and control appear to be perceived at 5.6 Nm and 7.2 Nm which indicates that extremely high forces offer low levels of comfort and control.

The pattern in Figure 5.4c for the Straight Comfort & Control cluster reveals that participants perception of ergonomics and naturalness of feedback torque increases from 0 Nm to a peak at 0.8 Nm, gradually decreasing at 2.4 Nm and 4 Nm and then significantly dropping at 5.6 Nm and 7.2 Nm. The cluster involves items such as Straight Control and Straight Comfort which indicates participants’ ability to perceive comfort and control with changes in feedback torque while driving on straight sections of the circuit. Presence of such items and their overall relationship with comfort and control reiterate the point that comfort and control are perceived together.

The pattern in Figure 5.4d for the Turn Comfort & Control cluster illustrates that participant perception of increased sturdiness as well as comfort and control in the curve segments of the circuit (referred by items Turn Comfort and Turn Control, respectively) increases from 0
Nm and peak at 2.4 Nm from which point it decreases gradually to 7.2 Nm. The relationship can be viewed as an inverted U-pattern. Since the cluster includes items relating to perceived comfort and control, it further reiterates that comfort and control are not distinct. The pattern in comparison with the Straight Comfort & Control pattern in Figure 5.4c shows that 2.4 Nm is perceived to offer more comfort and control during cornering than in the case of driving in straights, where 0.8, 2.4 and 4 Nm are perceived to offer similar amount of comfort and control. This suggests that drivers are more sensitive in their perception of comfort and control when significant steering actions need to be performed (in order to take turns) as opposed to driving in a straight line where only minimal corrections of the steering wheel are required. Therefore conventional steering systems that already offer higher feedback torque during cornering when compared with on-center driving (by making feedback torque a function of steering angle) are perceived to provide optimal comfort and control. The findings further suggest that if such a conventional steering system had been used in the experiment, there might not have been two distinct clusters for perceived comfort in on-center driving and turning, but we would instead have just two clusters – Overall Comfort & Control and Physical Effort. Hence items specific to steering conditions, such as on-center driving and turn taking, can be excluded from questionnaires that assess perceived comfort and control if the feedback torque on the steering wheel is varied as a function of steering angle.

On observation of Figures 5.4a, 5.4c and 5.4d, it can be concluded that comfort and control are perceived to be the highest in the 0.8-2.4 Nm region with a sharp drop on either side at 0 Nm and 4Nm followed by 5.6 Nm and 7.2 Nm, which are perceived to offer the least comfort and control.

The relationship between the Physical Effort cluster and feedback force as seen in Figure 5.4b shows that physical effort monotonously increases with increases in force. This shows that participants were able to clearly sense the different force levels offered to them. The absence of items relevant to comfort and control in this cluster as seen in Table 5.2 suggest that participants’ perception of comfort and control involve aspects apart from physical effort.

Looking at the Comfort & Control cluster in Table 5.2, it becomes evident that driver perception of comfort and control may not be significantly different from each other. Items in the cluster further suggest that perception of comfort and control may be influenced by how operable, normal, doable and pleasurable a feedback feels to the driver. The presence of Normal in the Comfort & Control cluster suggests that driver perception of comfort and control may significantly rely on the feedback that drivers have been familiar with. During interviews conducted in the pilot study, ‘Normal’ was used by participants to describe forces that they were most familiar with and used to in driving their cars on normal roads. This goes
on to suggest that feedback settings that differ considerably from one’s own perception of normality may impact their judgment of comfort and control that a setting may offer.

Presence of items such as Mental Effort, Frustration and Stress in the same cluster as Overall Comfort & Control suggests that perception of comfort and control may involve aspects relating to the cognitive processing abilities. And since they negatively correlated with items such as Operable, Normal and Doable in the same cluster, it suggests that increased comfort and control is perceived when the feedback torque does not require significant cognitive resources to perform the steering maneuver.

Based on discussions emerging from the cluster analysis, explained variance from data and semantic meaning of the items, a questionnaire to understand the amount of comfort and control that is perceived with different steering settings must include the following items: Comfort, Control, Normal, Operable, Pleasurable, Mental Effort and Stress from the Overall Comfort & Control cluster and Heavy and Physical Effort from the Physical Effort cluster. And as discussed earlier, items relating to specific steering conditions in the Straight Comfort & Control and Turn Comfort & Control clusters can possibly be excluded if feedback torque applied on steering wheel mimics conventional steering systems. It is important to note that the analysis performed contained missing data from 10 participants for 7 of the 27 attributes that were used, and this may have induced a correlation bias in the cluster analysis and influenced the amount of variance explained in the data. Therefore the amount of variance explained for items such as Physical Effort, Mental Effort and Pleasurable, which are among seven attributes with missing data, may vary from values seen in Table 5.2 if data from the missing participants were available. However, high levels of variance explained in data from 20 participants for these items ($R^2 \geq 0.75$ as seen in Table 5.2) reflect the need for their inclusion in questionnaires for experiments that study perceived comfort and control with different steering settings.

5.4 PERFORMANCE RESULTS AND DISCUSSION

The discussion in this chapter thus far shows that perceived comfort and control vary with different levels of feedback torque and that there are several underlying attributes which influence judgments on comfort and control. Performance will now be investigated to study how drivers perform with the different levels of feedback torque and to also observe whether performance patterns map on to the ratings for perceived comfort and control. In a study conducted by Liu & Chang (1995) it had been found that feedback torque had a significant effect on steering performance (observed by analyzing steering wheel angle deviations). The study however, tested only two conditions in which one had feedback torque and the other did not. Toffin et al., (2007) conducted a study with more feedback torque conditions to study performance. While the study found that drivers did not alter
their steering control behavior with the different levels of force feedback, the feedback torque conditions ranged only between 0 Nm to 4 Nm and did not offer constant feedback torque. Lack of constant feedback torque meant that drivers experienced varying levels of force as they were driving. The study also only used five participants and investigated performance after the first two curves with the different feedback torque conditions.

By providing six distinct levels of torque in the range of 0 Nm to 7.2 Nm, this study provides a more comprehensive view of the impact of variations in feedback torque on steering performance.

5.4.1 Performance Metrics

The following metrics were used to study steering performance: Standard Deviation of Steering Wheel Angle (SDST), Standard Deviation of Lateral Position (SDLP) and Steering Wheel Reversal Rates (SRR). These three standard metrics are commonly used to investigate steering performance (Krajewski, Somme, Trutschel, Edwards & Golz, 2009). We used them to provide a comprehensive analysis of performance while carrying out cornering and post-cornering stabilization maneuvers within a lane.

SDST is a standard metric that indicates the amount of deviation made by the driver on the steering wheel. Lower values of SDST indicate that drivers are able to maintain lateral control of the vehicle with fewer and/or smaller corrections of the steering wheel (Daniela, Caterina & Lucal, 2009). Higher values of SDST indicate that drivers make more and/or larger corrections on the steering wheel to maintain lateral position. In order to study how the level of feedback torque influences the need for corrections, SDST was used.

SDLP provides information pertaining to the magnitude of the deviation from the mean lane position for each participant over a specified part of the driving track. By computing SDLP it is possible to measure the degree of deviation from the mean lane position and study if it varies with feedback torque. High SDLP values are indicative of increased driver errors and poor lateral control performance (Knappe, Keinath & Meinecke, 2007). SDLP was hence chosen to study how varying the magnitude of feedback torque on the steering wheel affects lateral control performance.

SRR is another metric used to study performance within a lane. SRR is computed by calculating the number of steering wheel reversals beyond a defined range of movement, referred to as gap size, per unit of distance (SAE J2944, 2013). The metric is commonly used in studying task difficulty and performance with secondary tasks (Markkula & Engstrom, 2006 and McDonald & Hoffmann, 1980). SRR was computed in this study to explore the
effect of feedback torque on steering performance in pure steering mode i.e., in the absence of a secondary task. A gap size of one degree was used in this study to detect even small reversals of the steering wheel.

5.4.2 Performance Results and Discussion

Data from the driving circuit were organized separately for corners and post-cornering straight segments to study steering performance during and after cornering, respectively. Of the 11 corners and post-corner straight segments in the driving circuit shown in Figure 5.3, data from the final two corners (C10 and C11) and post-corner straight segments were excluded due to missing data.

Segment boundaries for the corner and post-corner straight segments were aligned with the exact beginning of the corner and post-corner straight segments. Checks indicated that the boundaries were accurate, meaning that cornering segments capture cornering activity by the driver and post-corner segments contain data after the driver has completed cornering. Data in the post-corner segments capture stabilization of the vehicle back to on-center handling after cornering and subsequent straight-line driving. In the post-corner straight segments, it was found that the stabilization of the vehicle occurred during the first 50 meters. Therefore data from the first 50 meters after exiting a corner were extracted and used for subsequent analysis for the post-corner straight segments.

Shapiro-Wilk tests were first performed to determine if the data in straights and corner segments followed a normal distribution. Results indicated that data for all the dependent variables 1) Standard Deviation of Steering Wheel Angle (SDST) 2) Standard Deviation of Lane Position (SDLP) and 3) Steering Wheel Reversal Rate (SRR) were non-normally distributed. Non-parametric tests were therefore adopted for subsequent analyses of data.

A Kruskal-Wallis test was applied to the data to determine if there was a significant effect of force on the dependent variables. Results from the test revealed that there was no effect of force on any of the dependent variables in the cornering maneuvers indicating that performance in corners did not vary across the different feedback torque levels. However, in the first 50 meters in the post-corner straight segments, results from the Kruskal-Wallis test showed that changes in feedback torque had a significant effect on SDST (H(5) = 11.146, p < .05) and SDLP (H(5) = 27.237, p < .05) but not on SRR. Since significant effects of changes in feedback torque were observed in the post-corner straight segments and not in corners, results reported further in this chapter investigate effects of feedback torque in the post-corner straights where the vehicle was stabilized after cornering.
Results for SDST in the post-corner straights are shown in Figure 5.5. As can be seen, in the post-cornering straight segments, SDST decreases with an increase in feedback torque from level 1 to level 4, and does not decrease further after level 4. Results of the Mann-Whitney U test on SDST (Table 5.5) in the post-cornering straight segments show lack of significant differences across levels providing feedback torque (Levels 2 - 6). As can be seen, only the differences between Level 1 and Level 4, Level 1 and Level 5, Level 1 and Level 6 are significant.

Results for SDLP in the post-corner straights are shown in Figure 5.6. As can be seen, the deviation in lane position is relatively high for Levels 1 and 6, and lower for intermediate Levels 2, 4 and 5. Unexpectedly, SDLP is also relatively high for the intermediate Level 3. Mann-Whitney U tests, that compare mean ranks, were performed for the post-cornering straight segments as a post-hoc test to compare feedback torque levels pairwise. Results of the test are shown in Table 5.6. As can be seen, SDLP for Level 1 is significantly different from Levels 2-5 but not from Level 6.
Table 5.5. Mann-Whitney U Tests On SDST In Straights.

<table>
<thead>
<tr>
<th></th>
<th>Level1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
<th>Level6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;*</td>
<td>&gt;*</td>
<td>&gt;*</td>
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</tr>
<tr>
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<td>&gt;</td>
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<td></td>
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</tr>
<tr>
<td>Level 4</td>
<td>&lt;</td>
<td>&lt;</td>
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</tr>
<tr>
<td>Level 5</td>
<td>&gt;</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Level 6</td>
<td></td>
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</tr>
</tbody>
</table>

* Indicates significant differences ($p < .05$)

Figure 5.6. Average SDLP in the different Feedback Torque Levels

The lack of significant differences in SDLP and SDST between most of the feedback torque levels suggests that participants could easily adapt to differences in feedback torque. To explore adaptation effects, data from the first 50 meters in post-corner straight segments were analyzed sequentially i.e., from the first post-corner straight segment to the 9th post-corner straight segments. SDLP and SDST computed from the data for the six different feedback torque levels across the 9 segments are as shown in Figure 5.7 and Figure 5.8, respectively.
Table 5.6. Mann-Whitney U Tests On SDLP In Straights

<table>
<thead>
<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
<th>Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>&lt;*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td></td>
<td>&lt;</td>
<td></td>
<td></td>
<td></td>
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<td>Level 4</td>
<td></td>
<td></td>
<td>&gt;</td>
<td></td>
<td></td>
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<tr>
<td>Level 5</td>
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<td></td>
<td>&gt;</td>
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<tr>
<td>Level 6</td>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

* Indicates significant differences (p < .05)

The SDST plot shown in Figure 5.7 shows that SDST drops from post-corner Segment 1 to post-corner Segment 5, then increases for segment 6 and decreases for segments 7 and 8 to level out for segment 9. The pattern for SDST can be understood by observing both the speed patterns within segments (Figure 5.9) and the radius of curvature of corners preceding the nine segments as shown in Table 5.3. Inspection of Figure 5.9 and Table 5.3 indicate that as cornering radius is increased, participants drive faster and also there are fewer and/or smaller variations in steering wheel angle, as evidenced by increased speed and lower SDST in Segments 5, 8 and 9, respectively.

It can be seen from Figure 5.8 that SDLP for Level 1 is higher than the other levels for most post-corner segments, confirming the results from the Mann-Whitney U test. Also it can be seen that, across levels, there is an improvement in performance from the first to the second segment, but no further improvement beyond segment 2.
This relationship between SDST and driving speed indicates that speed in post-cornering segments is directly related to curve radius, and that SDST is directly related to speed. Closer comparison of Figures 5.7 and 5.9 indicate that the decrease for SDST from Levels 1 to 4 is relatively large, comparing to the differences in speed for these segments. This relatively large decrease in SDST, not accounted for by differences in speed, may then be indicative of an adaptation effect, as was also hypothesized for SDLP in relation to the data in Figure 5.8.
CONCLUSION

The study was able to successfully explore the attributes that define perceived comfort and control and also the relationship between the two with variations in feedback torque. The study shows that subjectively assessed comfort and control are mutually dependent on each other and that their relationship with feedback torque is non-linear. The study also finds that driver perception of comfort and control is related to what drivers perceive as normal based on their existing driving experience. This therefore suggests that drivers rely on a personal baseline to judge comfort and control and this may significantly impact assessment of settings tested and developed for steer-by-wire systems. The reliance on a personal baseline indicates that participant familiarization with new settings is essential prior to evaluation. The study also shows that comfort is not so much related to physical effort but also with the feeling of control. Further, the study contributes in developing a questionnaire to assess perceived comfort and control of steering systems. The study also provides designers with insights on what regular drivers convey when they state to have perceived a certain level of comfort and control.

From the performance results we conclude the following. Overall, absence of feedback torque (Level 1) significantly affects driving performance adversely, as measured both by SDLP and SDST. There may be a further increase in performance with increases in feedback torque, as measured by SDST, but this was not paralleled by the results for SDLP. Also, there was a decrease in performance again with a high level of feedback torque (Level 6) as measured by SDLP, but this was not paralleled by findings for SDST.
Since SDLP and SDST both reflect control behavior, it may be asked how the findings for the objective measures SDLP and SDST compare to the findings for subjective control. Patterns for SDLP and SDST shown in Figure 5.5 and Figure 5.6 are not simply the inverse of the pattern for subjective ratings of perceived comfort and control in these straight segments as shown in Figure 5.4a. It can be seen in Figure 5.4a that perceived comfort and control increase from Level 1 to Level 2, continues to remain high at Level 3, following which it decreases sharply after Level 4 and drops to its lowest value at Level 6. The pattern resembles an inverted U shape with a sharp drop-off at Level 6. In Figure 5.5, SDST is high at Level 1 and remains consistently low in Levels 2 to Level 6. In Figure 5.6, SDLP decreases at Level 2, but increases at Level 3, following which it decreases again at Level 4 and increases at Level 6. If the SDLP values remained low at Level 3 and SDST values increased in Level 5 and in Level 6, then it would suggest that subjective ratings of comfort and control have a direct relationship with performance. Since the pattern of performance in the different feedback torque levels does not mirror the pattern of perceived comfort and control, there is an indication that levels of feedback torque which are felt as providing most control and comfort are not necessarily also the levels which give rise to best performance as measured by SDST and SDLP.

In regards to drivers being able to quickly adapt to the different levels of feedback torque, in the current study drivers only had to perform the primary task of driving and no secondary tasks had to be performed. Without a secondary task, drivers were not burdened cognitively and this may have allowed them sufficient time and ability to adapt their motor control task of steering to the different levels of feedback torque, although there is an exception with Level 1 (no feedback torque), where performance was clearly lower than for the other feedback levels. A question therefore arises as to whether drivers can quickly adapt to different feedback torque levels when cognitive resources are burdened with performing secondary tasks. The next study aims to answer this question.
CHAPTER 6

The Effect of Cognitive Load on Adaptation to Differences in Steering Wheel Feedback Torque Level

This chapter is based on:

6.1 INTRODUCTION
It appears obvious that a complete absence of feedback torque and very high feedback torque make it difficult for a driver to maintain control and produce good steering performance. However, in the study in Chapter 5 it was found that drivers can adjust quickly to different feedback torque levels on the steering wheel, even for such extreme levels as 0 Nm and 7.2 Nm feedback torque under normal driving conditions. Driving performance, measured objectively using standard metrics such as Standard Deviation of Lateral Position (SDLP), Standard Deviation of Steering Wheel angle (SDST) and Steering Wheel Reversal Rates (SRR,) did not vary between 0.8 Nm and 7.2 Nm. It was also found that drivers were able to quickly adapt to feedback torque levels in the 0 Nm – 7.2 Nm range, producing similar levels of performance as with normal feedback torque levels already after the first corner. This was taken as an indication that drivers learned quickly to compensate for non-normal levels of feedback torque. In the discussion of results in Chapter 5, it was hypothesized that the low cognitive load associated with driving in relatively quiet traffic conditions may have enabled drivers to learn quickly and in the study presented in this chapter, this explanation is put to test by means of introducing a second task.

Under normal driving conditions, in Michon’s (1985) terms, steering is an operational task, involving a highly over-learned visuo-motor task, which requires conscious control only at the initial stages of learning to drive (think of your very first driving lessons). However, it may be assumed that, for extreme feedback torque levels such as zero feedback torque and very high feedback torque, that is, levels of feedback torque deviating substantially from levels which drivers are used to, some form of conscious control comes into play again. In particular, the assumption is that in the case of zero feedback torque, when making a cornering maneuver, the driver needs to suppress the tendency to provide the normal level of input to the steering wheel, in order to prevent oversteering. Similarly in the case of extremely high feedback torque, when making a cornering maneuver, the driver need to suppress the tendency to provide the normal level of input to the steering wheel, in order to prevent understeering. Since these extreme situations are not familiar to the driver, it appears plausible to assume that some form of conscious control (or in Baddeley & Sala’s (1996) term executive control) is involved in these cases, comparable to the situation of novice drivers who are learning to steer. Furthermore, it may be assumed that drivers learn quickly to compensate for the tendencies applicable under normal conditions. Technically, it would translate into adjusting the connection between the visual input and the motor output. From a cognitive engineering perspective, it would mean that drivers simply give a bit more effort to adjust to the extreme situation.

If this reasoning is correct, it should be possible to impede or slow down the adjustment to extreme conditions by increasing the cognitive load, for instance by imposing a secondary
task on the driver. If the driver needs to perform a secondary task, it might take longer for him to compensate for the behavioral patterns applicable under normal conditions. The net result would be that he tends to give too little input with an extremely high level of feedback torque, resulting in understeering for the first few corners. Similarly, he might tend to give too much input with zero feedback torque condition, resulting in oversteering for the first few corners. In the study presented in this chapter, we put this reasoning to test by investigating the effect of a secondary task increasing the cognitive load for the driver on the driving performance. We predict that, under secondary task conditions, the steering performance for extreme feedback torque conditions will be affected more than for normal feedback torque levels, which may not be affected at all, and that the rate of adaptation to extreme feedback torque levels will be slower.

The hypothesis was tested by conducting a study with similar experimental conditions used in Chapter 5, but with the addition of a secondary task increasing the cognitive load. Performance effects are measured by standard metrics for lateral performance such as Standard Deviation of Lateral Position (SDLP), Standard Deviation of Steering Wheel Angle (SDST) and Steering Wheel Reversal Rates (SRR). Since it has been shown before (de Waard, 2002) that drivers may also adjust to more difficult situations by decreasing the driving speed, Mean Driving Speed (MDS) will also be included as a performance metric.

6.2 METHOD

6.2.1 Experimental Design

The experiment followed a within-between subjects design with seven experimental conditions. Six of the seven experimental conditions included a secondary task. Forces on the steering wheel were varied in each of the conditions to feedback torque levels shown in Table 6.1. The feedback torque was varied between 0 Nm and 7.2 Nm in order to allow participants to experience a wide range of forces that included feedback forces normally encountered in a vehicle as well as extremely low and high forces, similar to what was done in the previous study. All participants received these six conditions in a randomized order to prevent ordering effects. The seventh condition was used to measure baseline performance without the secondary task. To prevent fatigue, each participant received only one level of feedback torque from the six levels in the baseline condition. The feedback level for the baseline measure was pseudo-randomly assigned for each participant, making sure that across participants an equal number of observations were obtained for each baseline condition. The experimental design therefore allows baseline performance in the six levels to be studied between subjects and performance with secondary task in the six levels to be studied within subjects.
6.2.2 Participants

Twenty four (N = 24) subjects who had a minimum of 1.5 years of driving experience were recruited to take part in the study. Only Dutch citizens were recruited as the secondary task required familiarity with the Dutch language. Participants recruited consisted mostly of students affiliated with Eindhoven University of Technology. Of the 24 subjects, 14 were male and 10 were female. Participants had a mean driving experience of 4.4 years (SD = 2.0) and a mean age of 24.5 years (SD = 2.1).

6.2.3 Equipment

The driving tasks were performed in the fixed-base Green Dino driving simulator. A brushless DC motor with 8 Nm rated torque and 24 Nm peak torque fitted to the simulator was controlled in the same way as in the earlier study discussed in Chapter 5 to produce six levels of feedback torque. The six levels of feedback torque are shown in Table 6.1.

<table>
<thead>
<tr>
<th>Feedback torque Level</th>
<th>Percentage of Rated Torque (8Nm) in %</th>
<th>Actual Torque Produced (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Level 2</td>
<td>10</td>
<td>0.80</td>
</tr>
<tr>
<td>Level 3</td>
<td>30</td>
<td>2.40</td>
</tr>
<tr>
<td>Level 4</td>
<td>50</td>
<td>4.0</td>
</tr>
<tr>
<td>Level 5</td>
<td>70</td>
<td>5.60</td>
</tr>
<tr>
<td>Level 6</td>
<td>90</td>
<td>7.20</td>
</tr>
</tbody>
</table>

6.2.4 Driving Task

The experimental task required participants to navigate a 3.6 Km circuit shown in Figure 6.1. Segment details of the corners used for data analysis are shown in Table 6.2.
The circuit required participants to begin driving from the ‘Start’ position and execute corners of varying radii before coming to a stop. The circuit had low density traffic in the opposite lane to simulate a realistic countryside driving environment and prevent intentional lane departures. There was no traffic in the driving lane. Participants were instructed to keep to the center of the lane while driving through the circuit. Participants were given control over their driving speed but were instructed to drive at speeds at which they would drive in a similar scenario on actual roads.
6.2.5 Secondary Task

A Running Memory Span task (N-back task) which continuously consumes cognitive resources (Kusak et al., 2000) was the secondary task used in the study. The N-back task is a commonly used task to increase cognitive workload and has been used for the same purpose in driving studies as well (US Department of Transportation Technical Report Dot HS 811 463, 2011). In an N-back task, subjects are required to recall the final N values of an auditory sequence containing numbers or letters. With higher values of N, the workload is increased. From a pilot study, it was decided to have N = 4 i.e., a 4-back task for the main study. Dutch letter names were used in the sequences for the 4-back task. Each sequence contained letter names in random order. The spacing between letter names in each sequence was set at 1.5 seconds, as this appeared to make the task neither too easy nor too difficult. Unlike a traditional 4-back task, participants in the study were not required to call out loud the final 4 characters. Instead, they were required to call out loud whether a probe letter played after a sequence was present in the last 4 letters of the sequence that was played back. The probe letter was preceded with an 800Hz short tone that signaled the end of a sequence.

Participants were instructed to call out loud “Yes (Ja)” or “No (Nee)” to indicate whether the probe letter was present or not in the last 4 letters of the sequence. For instance, participants would hear k – b – a – f – p – z – u – m – s – ^f (where ‘^’ denotes the warning tone, ‘f’ is the probe and ‘–’ denotes a 1.5 second interval) and participants had to indicate whether f was one of the last four characters. In the example, the correct response is “No”. Participants had 5 seconds to call out their response after which the next random letter sequence was played. Responses from participants were recorded by hand. 6 playlists with 10 random letter sequences and probes were created for the 6 experimental conditions. Lengths of the random letter sequences were also randomized between 5 and 14 characters to make the occurrence of the probe unpredictable. Pre-recorded digital read-outs of Dutch letter names from a Dutch language course (Broek, 2010) were used. All sequences were created using the Audacity freeware software.

6.2.6 Procedure

Upon obtaining informed consent, demographic information such as gender and driving experience were collected from participants. Then they did a familiarization trial to get familiar with the experimental set-up. Familiarization involved participants driving on the driving task circuit for approximately five minutes with a mid range feedback torque level and no secondary task. Next, participants performed the N-back task in isolation to ensure they understood the secondary task. Then participants were instructed to perform the driving task under the seven experimental conditions. Participants were asked to perform equally well on both driving and the secondary task. On completion of the driving task under
each experimental condition, participants were asked to provide a rating of perceived mental effort they experienced in that condition on the RSME (Rating Scale for Mental Effort) scale (Verwey & Veltman, 1996). Simulator data were logged at a rate of 20Hz. SDLP and SDST were calculated as done in Chapter 5 in each individual segment for each individual run. SRR was calculated over distance as per Society of Automobile Engineers (SAE) Standard J2944 for a gap size of 1° (degree). In addition to SDST, SDLP and SRR, mean driving speed (MDS) was also computed for individual segments and included as the fourth dependent variable to test the hypothesis. The duration of the experiment was approximately 60 minutes per participant.

6.3 RESULTS AND DISCUSSION

Data from the six experimental conditions which included the secondary task were first analyzed. As in Chapter 5, data from the driving circuit were organized separately for corners segments and the first 50 meters in the post-cornering straight segments to study cornering and post-cornering vehicle stabilization, respectively. Since data visualization showed that vehicle stabilization takes place in the first 50 meters after cornering, it was decided to extract dependent variables only for this distance in the post-cornering straight segments. Subsequent references to post-corner straight segments in the paper therefore only indicate stabilization performance in the first 50 meters after cornering.

Shapiro-Wilk test was first performed to determine if the data in corner and post-corner straight segments followed a normal distribution. Results indicated that data for all the three dependent variables 1) SDST 2) SDLP 3) MDS and 4) SRR were non-normally distributed. Non-parametric tests were therefore adopted for subsequent analyses of data.

Since the experimental design for the six experimental conditions with the secondary task followed a within subjects design, Friedman’s ANOVA was applied to data from corners and post-corner straight segments to determine if there was a significant effect of force on the dependent variables. Results from the test are shown in Table 6.3. It can be seen that with the secondary task, there was an effect of force on SDST, SDLP and MDS in both the corners and post-corner straight segments. In the study conducted earlier, effect of force was significant only in the post-corner straight segments. With a secondary task inducing cognitive workload, the driving performance not only differs while stabilizing the vehicle in post-corner segments but also in the cornering maneuvers with the six different feedback torque levels.

The effect on SRR was not significant and this indicates that steering reversal rate was the same for the six feedback torque levels. With significant effects observed with SDST and SDLP, the lack of a significant effect on SRR suggests that although the number of reversals remained the same between levels, the magnitude of steering wheel movement after a
reversal differed between different levels. The results for SDST, SDLP and MDS are shown in Figures 6.2, 6.3 and 6.4, respectively. The results of post-hoc analyses with Wilcoxon Matched-Pairs Signed-Ranks test are shown in Tables 6.4, 6.5 and 6.6. According to the hypothesis, the extreme force Levels 1 and 6 should be strongly affected by the secondary task, comparing to the mid-range Levels 3 and 4. As can be seen in Figures 6.3 and 6.4, for the post-corner segments, Levels 1 and 6 have indeed higher SDLP and SDST, but this does not apply for the corner segments. Furthermore, looking at the results of the post-hoc tests, Levels 1 and 6 are not clearly different from the other levels. While SDST for Level 1 is significantly different from Levels 2, 4 and 5 in post-corner segments, this is not the case for Level 6 (see Table 6.4). With respect to SDLP in post-corner segments, Level 1 is significantly different from Levels 2, 4 and 5, but again the results for Level 6 do not indicate that it is clearly different from the mid-range levels (see Table 6.5).

<table>
<thead>
<tr>
<th>Table 6.3. Results From Friedman’s ANOVA On Dependent Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corner Segments</strong></td>
</tr>
<tr>
<td>SDST</td>
</tr>
<tr>
<td>SDLP</td>
</tr>
<tr>
<td>MDS</td>
</tr>
<tr>
<td>SRR</td>
</tr>
<tr>
<td><strong>Post-Corner Straight Segments</strong></td>
</tr>
<tr>
<td>SDST</td>
</tr>
<tr>
<td>SDLP</td>
</tr>
<tr>
<td>MDS</td>
</tr>
<tr>
<td>SRR</td>
</tr>
</tbody>
</table>
Figure 6.2. SDST across participants in the six Feedback Torque Levels with 95% confidence interval bars

Figure 6.3. SDLP across participants in the six Feedback Torque Levels with confidence interval bars
Figure 6.4. MDS across participants in the six Feedback Torque Levels with 95% confidence intervals bars
Table 6.4. Wilcoxon Signed-Ranks Test For SDST

<table>
<thead>
<tr>
<th>Corners</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
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<td>Level 2</td>
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<td>Level 6</td>
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</table>

<table>
<thead>
<tr>
<th>Post-Corner Straights</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Level 5</th>
<th>Level 6</th>
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<td>Level 6</td>
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* Indicates significant differences (p < .05)
### Table 6.5. Wilcoxon Signed-Ranks Test For SDLP

#### Corners

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<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
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#### Post-Corner Straights

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<tr>
<th></th>
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<th>Level 5</th>
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<tbody>
<tr>
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* Indicates significant differences ($p < .05$)
Table 6.6. Wilcoxon Signed-Ranks Test For MDS

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<tr>
<th></th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
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<th>Level 5</th>
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<tbody>
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<td>Level 6</td>
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* Indicates significant differences ($p < .05$)

The results for the corner segments show that neither Level 1 nor Level 6 are clearly different from the mid-range levels, although for Level 6 significant differences can be found with some of the mid-range levels. However, inspection of Figure 6.2 shows that the mid-range levels for corner segments in fact show higher SDST than the extreme force levels. With respect to SDLP, as can be seen in Figure 6.3, Level 6 has higher SDLP than the other levels, but only the difference with Level 4 is statistically significant as shown in Table 6.5, and Level 1 does not show higher SDLP. Thus, the pattern of results does not confirm the hypothesis that extreme feedback torque levels are strongly affected by a secondary task, comparing to the mid-range levels.
As was mentioned in the introduction, an alternative way for drivers to deal with a difficult task is by compensating through speed reduction. If we inspect Figure 6.4 and Table 6.6, we see no consistent differences in Mean Driving Speed between Levels 1 and 6 on the one hand and the mid-range Levels 3 and 4 on the other hand. For the corner segments, MDS for Level 1 is significantly different from Levels 3, 5 and 6, but again level 6 is not consistently different from the mid-range levels. For post-corner segments, Level 1 has significantly lower MDS than Levels 3, 4, 5 and 6, but Level 6 is not consistently different from the mid-range levels.

In sum, for the corner segments, Level 6 is higher only for SDLP (but not significantly so as seen in Table 6.5), while Level 1 has lower SDST and SDLP than most other levels. Also, for corner segments, Level 1 has lower MDS than the other levels, but this is not the case for level 6. For the post-corner segments we find that SDST and SDLP for Level 1 are higher than the mid-range levels and that MDS is lower; for level 6, SDST and SDLP are higher than the mid-range levels but not always significantly so, and MDS is not consistently lower than the mid-range levels.

The findings from SDST, SDLP and MDS thus far suggest that even with added cognitive workload by performing the secondary task, the performance with extreme levels of force, Level 1 and Level 6, is not consistently worse than the intermediate feedback torque levels, although there is a clear trend for Level 1 to be worse than other levels of feedback torque.

In the previous study, performance evidence was found that drivers could quickly adapt to extreme feedback torque levels, by analyzing performance as a function of serial position of the segment. While the hypothesis states that a secondary task would prevent such adaptation from occurring, a less strict hypothesis would be that adaptation would be slowed down, comparing to a baseline condition with secondary task. In order to check this less stricter version of the hypothesis, SDST, SDLP and MDS were calculated for the individual segments. As in the previous study this adaptation effect was observed particularly in the post-corner segments, the current analysis is also limited to the post-corner segments. With respect to the baseline, as explained in the Methods section, for reasons of participant fatigue each participant did only one run in the baseline condition. The feedback torque level for each participant was chosen randomly with the constraint that all six levels would be represented equally. With 24 participants, this means that data in each feedback torque level in the baseline condition are based on data from four participants.

Figures 6.5, 6.6 and 6.7 show MDS, SDST and SDLP values for the six different feedback levels with and without the secondary task. Similar to the previous study, in Figure 6.5 it can be seen that the driving speeds are different between segments, due to varying curve radius
preceding these post-cornering straights shown in Table 6.2. It may also be seen from this figure that performance with the extreme feedback torque levels is not clearly different from the mid-range feedback torque levels. Friedman’s ANOVAs conducted on the data for the separate segments also showed that MDS did not significantly vary between the six feedback torque levels in segments 1, 2, 3, 4, 8 and 9. Although significant effects of force are noted in segments 5 ($\chi^2(5) = 12.71, p = .03$) and 7 ($\chi^2(5) = 13.17, p = .02$), the lack of significance in the preceding segments (1,2,3,4) leads us to conclude that participants were able to quickly adapt to the six levels of feedback torque and maintain similar driving speeds even while performing a secondary task.

![Figure 6.5. MDS across participants for the six feedback torque levels with and without the secondary task in the post-corner straight segments.](image)
Figure 6.6. SDST across participants for the six feedback torque levels with and without the secondary task in the post-corner straight segments.

Figure 6.7. SDLP across participants for the six feedback torque levels with and without the secondary task in the post-corner straight segments.

It is however interesting to note that the majority driving speeds are higher without the secondary task and this suggests that combination of the driving tasks and secondary task is experienced as more difficult, resulting in compensation by decreasing the speed when performing a secondary task.

SDST values within each segment are shown in Figure 6.6. Unlike MDS, these values have an inverse relationship with curve radius i.e., when the curve radius is small in the preceding corner segment, the SDST is higher in the post-cornering straight segment and vice versa. The inverse relationship can be observed by comparing Figure 6.6 to curve radius in Table
6.2. Figure 6.6 displays a learning curve, where after Segment 1, in which the deviations are the largest, the adaptation is quick and participants accommodate to the six different feedback levels. Friedman’s ANOVAs conducted on the data for the separate segments showed that SDST did not vary significantly except for segment 6 (χ²(5) = 11.19, \( p = .04 \)). This finding that there are no distinctive patterns for the different levels of feedback torque leads us to conclude that the rate of adaptation is the same for the six different feedback torque levels while performing the secondary task.

SDLP values shown in Figure 6.7 also point towards quick adaptation to the extreme feedback torque levels, comparing to the mid-range feedback levels, after the first post-cornering straight Segment 1, both for conditions with and without the secondary task. It can be seen that SDLP is higher in Segment 3 and Segment 4 for Level 1 and Level 6, respectively. However, this does not provide convincing evidence towards differential (slower) adaptation effects, as they are not preceded or followed by consistently higher values for the preceding and following segments, and could be the result of fewer (only 4) data points for the baseline condition. Friedman’s ANOVAs conducted on the data for the separate segments for SDLP also reveals lack of significant effect of force in segments 1, 2, 3, 5, 6, 7 and 9. Presence of significant effects at segments 4 (χ²(5) = 27.26, \( p = .00 \)) and 8 (χ²(5) = 17.45, \( p = .00 \)) could be a result of a single participant driving differently as again the baseline condition for the different levels of feedback torque have data only from four participants. This result further strengthens the interpretation that the rate of adaptation is the same for the six levels of feedback torque even while performing a secondary task.

The findings of the study presented thus far show that the addition of a secondary task does not affect driving performance. However, it is possible that drivers may have been prioritizing lane keeping performance at the expense of secondary task performance. To test if that was indeed the case, secondary task performance was analyzed by observing the percentage of correct answers recorded for the secondary task in each of the six feedback torque levels. The percentages of correct answers across participants in each level are as shown in Table 6.7.
Table 6.7. Percentage of correct answers in each feedback torque level for secondary task.

<table>
<thead>
<tr>
<th>Feedback torque Level</th>
<th>Percentage of Correct Scores across participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>70.7</td>
</tr>
<tr>
<td>Level 2</td>
<td>80.4</td>
</tr>
<tr>
<td>Level 3</td>
<td>72.7</td>
</tr>
<tr>
<td>Level 4</td>
<td>70.1</td>
</tr>
<tr>
<td>Level 5</td>
<td>71.4</td>
</tr>
<tr>
<td>Level 6</td>
<td>73.4</td>
</tr>
</tbody>
</table>

A One-way ANOVA with repeated measures on the secondary task performance data showed that performance did not significantly differ between the levels of feedback torque (F (5, 343) = 0.87, p > .05). This finding therefore reveals that drivers did not adapt to the six levels of feedback torque by compromising secondary task performance. The mean mental effort ratings from the RSME scale are as shown in Table 6.8. The baseline scores are averaged across different levels of feedback torque.

Table 6.8. Mean RSME Ratings for Six Feedback Torque levels and the Baseline condition.

<table>
<thead>
<tr>
<th>Feedback torque Level</th>
<th>Mean RSME Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>62.00</td>
</tr>
<tr>
<td>Level 2</td>
<td>61.46</td>
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<tr>
<td>Level 3</td>
<td>64.42</td>
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<tr>
<td>Level 4</td>
<td>74.58</td>
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<tr>
<td>Level 5</td>
<td>75.92</td>
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<tr>
<td>Level 6</td>
<td>80</td>
</tr>
<tr>
<td>Baseline</td>
<td>23.71</td>
</tr>
</tbody>
</table>

As can be seen, there is more than “Rather Much Effort (RSME = 58)” with Level 1, Level 2 and Level 3 whereas there is “More Than Considerable Effort (RSME =72)” in driving with Level 4 and above while performing the secondary task. The mental effort ratings also show
that there is almost “Very Little Effort (RSME =27)” involved in driving without the secondary
task. Even with such differences in mental effort ratings, participants’ ability to adapt to
different levels of steering wheel feedback shows that cognitive load does not influence
adaptation.

6.4. CONCLUSION
The results lead us to conclude that cognitive load does not have an effect on adaptation to
extreme levels of feedback torque as predicted by the hypothesis. In other words, even in
the presence of a secondary task participants quickly and easily adapt to the extreme levels
of feedback torque and mid-range feedback torque levels. The conclusion is drawn from
segment-wise analysis of MDS, SDST and SDLP in conditions with the secondary task.

The study did find an overall effect of cognitive workload on driving performance with the six
different feedback torque levels. Cognitive workload produced an effect of force on driving
performance for both cornering and post-cornering maneuvers. However, even with
addition of cognitive workload, performance patterns in the extreme levels of torque (Level
1 and Level 6) remained similar to the other levels of feedback torque as seen in Figures 6.3,
6.4 and 6.7. Like in the earlier study without secondary task, performance with Level 1 was
poorer compared to other levels of feedback even after reducing driving speed.

In another study from the US DOT Report HS 811 463 (2011), the N-back task did not
influence lateral control performance. However, that study used 2-back tests and also did
not vary feedback forces on the steering wheel. In the current study drivers not only
performed a more difficult 4-back task, but they also had to adapt to changes in feedback
torque on the steering wheel. This again shows that drivers can easily adapt to handling
feedback torque changes on the steering wheel and that cognitive load has no effect in
adaptation. In other words, the study suggests that learning to deal with difficult feedback
torque levels does not involve conscious (executive) control as postulated in the
introduction. Alternatively, it is possible that the N-back task does not affect the type of
resources involved in adjusting to difficult feedback torque levels, and so with a more
challenging task it might still be possible to prevent adaptation to force levels that make the
driving task more difficult from occurring.

In regard to the transferability of the findings of the study to real-world driving, it should be
pointed out that the driving simulator used in the study is of the fixed-base type and does
not provide drivers with curve negotiation cues other than feedback torque, such as lateral
acceleration encountered in real life driving. The next set of studies conducted on a
prototype test vehicle overcome these limitations and aim to expand current understanding
of steering feel and performance with different steering wheel feedback settings.
Chapter 7

Mapping Physical Steering Parameters to Subjective Experience Attributes

Part I
7.1 INTRODUCTION

In SbW systems steering parameters modeling the behavior of the system can be modified to generate different experiences. The studies discussed thus far have focused mainly on force, a subjective experience attribute, which contributes to steering feel. It has been mentioned in Chapter 1 and in Chapter 2 that there are other subjective experience attributes which contribute to steering feel. The other subjective experience attributes also need to be studied to understand the subjective experiences that can be altered with a flexible SbW steering system. To understand how a particular subjective experience attribute can be varied, a mapping between the subjective experience attributes and physical steering parameters is required. The aim of the study presented in this chapter is to 1) understand how changes in steering parameters affect subjective experiences for the driver, 2) gain a broader understanding of steering feel in a realistic driving environment, and 3) study whether positive subjective experiences translate into improved driving performance.

In most studies, there has been limited focus on the subjective experiences and instead emphasis on driver and system performance when studying steering systems (Zschocke & Albers, 2008; Rothhämel, Ijkema & Drugge, 2011). Even while studying the subjective experiences, the focus has been on the subjective experience of driver performance rather than the experience of steering feel. In the case of SbW systems, much of the focus still remains on hardware selection and development with limited focus on driver perception of steering feel. But there have been few studies on subjective experiences and steering feel using cars that had conventional steering systems which are summarized in (Rothhämel, 2013). The studies were usually done using multiple passenger cars to study perception of steering feel with different steering settings. By using different cars, the steering feel measures could have varied not just based on the steering system but also on the dynamic properties of the vehicle thereby having too many variables influencing steering feel. The studies though were able to identify different dimensions, referred to as subjective attributes in this chapter, which are used to study steering feel. With SbW systems, these dimensions can be modified in the same car through changes in the steering model. A mapping between the dimensions and changes in the model could result in information that can be used to create customizable steering settings for driver based on desired levels of steering feel dimensions.

In the study presented in this chapter, subjective experiences were studied by varying steering parameters modeled after a conventional steering system as we wanted to test whether the effects of such on the steering feel need to be simulated in SbW systems. Among various steering parameters, the following five parameters were chosen as they were found to alter subjective experiences the most as detailed in the methods section of this chapter: 1) Power Assistance Gain 2) Boost Linearity 3) Torsion Bar Stiffness 4) Steering
Wheel Damping and 5) Steering Gear Ratio. The aim was to vary these parameters to study how they influenced the subjective experiences. Subjective experiences were recorded using a questionnaire and also through interviews. The questionnaire included steering feel attributes such as Force, Comfort, Control, Directness, Sensitivity, Return-to-center Feel, Road Feel and Sluggishness. The attributes were derived from earlier studies on the topic as mentioned before and also from pilot studies where participants were asked to actively think-out-loud about the experiences which varied when steering settings were changed. Attributes such as Comfort and Control were included to study them in steering conditions mimicking those found in conventional systems unlike previous experiments presented in this thesis which focused on specific levels of feedback torque alone.

Attempts were first made to improve the steering model on the existing driving simulator used in earlier studies and test whether the simulator with a realistic model could still serve as a suitable test platform for this study. The driving simulator is a more convenient test-platform in comparison to a test-vehicle in terms of logistic arrangements, experimental controls and safety protocols and hence was looked at as the first option. The Green Dino simulator used in earlier studies was therefore upgraded with a realistic steering model developed at the TU/e as part of two masters student projects (Orkutman, 2011; Sanchez, 2012). The steering model’s performance was validated to be similar to that of conventional steering systems. A pilot study with seven employees from Eindhoven University of Technology was conducted and all five parameters were varied in the steering model. Each of the parameters was varied from their minimum to maximum values individually while keeping other parameters at default (baseline) values. The minimum and maximum values were obtained after simulation tests using the steering model where the vehicle stability was being observed. The baseline values for the system are defined, by TNO (Verschuren & Zuurbier, 2004), in the model to simulate the steering feel in a similar vehicle when operated in non-SbW mode. The findings from the simulator were however not encouraging as manipulation of the parameters did not alter subjective experiences apart from Force. Participants mentioned that they had difficulty in perceiving speed, dynamic movement of the vehicle and the movement of the road wheels in the simulator. With the inability to perceive anything other than changes in Force, it was decided to not conduct the study in the simulator as it would not offer the desired mapping between subjective experiences and steering parameters.

With the driving simulator proving to be unsuitable as a test platform for components of steering feel other than force, a prototype SbW vehicle provided for the VERIFIED I & II projects was used as the test platform.
7.2. METHOD
7.2.1 Experiment Design

The experiment followed a within-subjects design where all participants were exposed to the same experimental settings. 10 experimental conditions were offered to participants. The 10 conditions were created by manipulating the following steering parameters to two distinct levels from the baseline setting: 1) Power Assistance 2) Boost Linearity 3) Torsion Bar Stiffness 4) Steering Wheel Damping and 5) Steering Ratio.

![Parameter Settings Diagram]

Figure 7.0. Experimental Settings for the 5 parameters.

The parameter settings are shown in Figure 7.0. As can be seen in this table, most parameters were manipulated to the maximum and minimum saturation points for stable operation in SbW mode except for Boost Linearity where baseline setting was already at minimum value. Therefore the test conditions for Boost Linearity are at 50% and max saturation value. The Steering Ratio parameter is another exception for which the settings did not go to the saturation points for safety considerations. A pilot study indicated that the settings that were chosen in this study, shown in Figure 7.0, were perceptually distinct from one another. In each condition only one parameter was varied while the others were
maintained at baseline condition in order to distinctly study the effect of changing a particular parameter on subjective experience and performance. Subjective responses on the questionnaire (as in Appendix B.2) were ratings comparing the test condition to the baseline condition. In the pilot studies it was found that participants were often providing ratings in comparison to the previous test condition and to avoid this and neutralize perception levels, the baseline condition was reintroduced prior to each test condition. Hence prior to receiving a test condition, participants were exposed to the baseline. Reintroduction of the baseline prior to the test condition ensured that participant ratings were not influenced by experiences from the previous test condition.

7.2.2 Equipment

7.2.2.1 BMW CarLab SbW Prototype

A BMW 318i that was converted to serve as a SbW vehicle (as shown in Figure 7.1) was used in the study. To achieve SbW operation, the conventional steering column was replaced by an assembly that contains two brushless DC motors for providing the feedback torque. Furthermore, an encoder was fitted to measure the steering wheel position. A torque sensor was incorporated to measure the driver torque. For safety purposes a normally closed electromagnetic clutch is installed that creates a fixed connection between the steering wheel and rack such that normal steering was returned in case of an emergency.

The rack actuation is done using a hydraulic servo system which consists of a hydraulic pump fixed to the crankshaft of the engine. This pump is connected to the conventional steering rack via a Moog servo valve. Control is done using a PID controller that compares the reference position provided by the steering system dynamics with the measured position of the steering rack. Forces from the tyres acting on the steering rack are measured by strain gauges on the tie-rods. For the real-time control a dSpace Autobox system was used.

Figure 7.1 Prototype Steer-by-Wire vehicle.
7.2.2.2 Steering System Dynamics

Due to the absence of a physical connection between the steering wheel and the front wheels, the SbW system offers complete freedom in providing both feedback torque and vehicle response to the steering wheel. To control this, a model of a conventional steering system is created in which various parameters can be influenced, see Figure 7.2. The model is based on the model described in Verschuren & Zuurbier (2004). Three distinct components can be defined. The steering wheel is the input device; with this the driver sets the desired path of the vehicle. It also serves as a feedback device and can provide the driver with information about the external forces acting on the tires. The steering wheel is connected to the front wheels via a torsion bar. This torsion bar is modeled as a spring with a small amount of damping. Finally, the steering rack connects the torsion bar, and thus the steering wheel to the front wheels. The ratio determines the amount of travel of the rack per revolution of the steering wheel. The steering system is modeled as a two degree of freedom model (Verschuren & Zuurbier, 2004).

The equations for this can be written as

\[ T_{sw} = k_{sc} (\delta - N y_{rack}) + d_{sc} (\dot{\delta} - N \dot{y}_{rack}) + d_{sw} \delta \]  
\[ m_{rack} \ddot{y}_{rack} = - k_{sc} (\delta - N y_{rack}) - d_{sc} (\dot{\delta} - N \dot{y}_{rack}) + F_{external} - \gamma F_{hydr} - d_{rack} \dot{y}_{rack} \]

where,

- \( T_{sw} \) – Feedback Torque on the Steering Wheel
- \( k_{sc} \) – Stiffness of Torsion Bar
- \( \delta \) – Steering Wheel Angle
- \( \dot{\delta} \) – Rate of Steer
- \( N \) – Steering Gear Ratio
- \( d_{sw} \) – Steering Wheel Damping
- \( d_{rack} \) – Rack Damping
- \( m_{rack} \) – Rack Mass
- \( y_{rack} \) – Rack Displacement
- \( \dot{y}_{rack} \) – Rack Acceleration
- \( \gamma \) – Parameter to scale amount of assist force
- \( F_{external} \) – Forces from the tires
- \( F_{hydr} \) – Hydraulic Forces

In words, from equation (1)

Steering Wheel Feedback Torque is determined by stiffness of the torsion bar, steering angle, rack displacement, steering gear ratio, damping of the torsion bar, damping of the steering wheel angle, rate of steer and rack velocity.

In words, from equation (2),

Forces on the Steering Rack are determined by mass of the rack, rack acceleration, rack velocity, stiffness of torsion bar, damping of the torsion bar, steering angle, rate of steer,
steering gear ratio, tyre forces and hydraulic forces which are dependent on $\gamma$. The hydraulic forces ($F_{\text{hydr}}$) are described in detail in the next section.

Figure 7.2. Layout of the Steering System

7.2.2.3 Hydraulic forces

The amount of hydraulic assist force $F_{\text{hydr}}$ is a function of the amount of torque the driver applies to the steering wheel (measured using sensors) and the external forces acting on the steering rack. This is implemented by considering equation (1) and neglecting the torsion bar damping. The torque is thus proportional to the rotational difference of the torsion bar. The boost curve used in this research is shown in Figure 7.3. As can be seen, the linearity of the response is a variable that can be influenced; more details on how this can be achieved in a conventional hydraulic power steering system can be found in (Roesth, 2007). Obviously, with the SbW system this property can be changed easily. Note that 0 % Boost Linearity is the default setting.
7.2.2.4 Parameter Selection

From equations (1) and (2) it is clear that numerous parameters can be changed to influence the feedback torque $T_{sw}$ on the steering wheel. For stability reasons the rack mass $m_{rack}$, the torsion bar damping $d_{tc}$ and the rack damping $d_{rack}$ are not changed. The parameters which are expected to influence the perception of steering feel are chosen for the study. The effect of changes of the power assistance and boost linearity parameters can be seen in Figure 7.4. It can be seen that there is a significant change in feedback torque with steering wheel rotation. The effects of changes to the torsion bar stiffness can be best explained by the frequency response of the system; with greater torsional stiffness, higher frequency vibrations reach the steering wheel and this means that there is greater feeling for the road. Steering wheel damping also changes the frequency response and also has influence on the returnability of the steering wheel. Finally, the Steering Ratio influences the directness response of the vehicle as a function of steering wheel angle. Based on the above considerations, the five parameters mentioned in Figure 7.1 are chosen.
7.2.3 Participants

14 participants comprising mostly of students and employees of Eindhoven University of Technology who were regular drivers and in possession of a EU driver’s license for a minimum of 2 years were recruited for the study. Of the 14 participants, 12 were male and 2 were female. Mean age and driving experience of the participants were 25.2 years (SD = 2.6 years) and 6.5 years (SD = 2.9 years), respectively.

7.2.4 Questionnaire

Subjective experiences were recorded on a questionnaire and through interviewing. The questionnaire was developed following a pilot study involving two expert drivers from the Department of Mechanical Engineering. In the pilot study, both drivers were initially probed about steering feel and were asked to provide subjective experience attributes that define good steering feel. In addition to recording information from open ended questions, questions with attributes related to steering feel based on literature, anecdotal evidence and previous experiments were included. Seven attributes (Comfort, Control, Stability, Precision, Road Feel, Required Effort and Response) were scored on a 5 points scale ranging from 1 = Very Low to 5 = Very High. Preference and Overall Steering Feel Rating were also studied from the questionnaire on a 10-point rating scale where 10 = most desired and 1 =
least desired. The questionnaire was administered following each of the test conditions listed in Figure 7.0 to rate different elements of steering feel. Both participants of the pilot study were instructed to also think out loud and list any additional attributes upon which they would like to rate the subjective experiences.

In the pilot study, responses from the open ended questions revealed that even experienced drivers found it difficult to articulate on steering feel based on previous experiences. However, when experiencing the test conditions, they were more detailed in talking about steering feel and associated attributes. Taking into account the results of the pilot study, the questionnaire was modified and included the following nine items to provide quantitative ratings for the test conditions: 1) Force 2) Road Feel 3) Sensitivity/Response 4 ) Sluggishness 5) Return-to-Center Feel 6) Directness 7) Control 8) Comfort and 9) Overall Steering Feel. The rating scale was also modified to ensure that comparisons to the baseline were easily recorded. A ten point dissimilarity rating scale ranging from -5 = Extremely Lower to +5 = Extremely Higher was used to indicate difference from baseline condition. Zero (0) was provided to indicate No Difference was noticeable from the baseline condition.

With a total of 10 experimental conditions, the questionnaire was administered 10 times for each participant.

7.2.5 Think-Out-Loud Audio Recordings

From pilot studies it was found that participants are at ease in articulating about steering wheel feedback and steering feel while driving and so participants in the study were asked to think-out-loud as they were performing the driving task. Those who were unable to spontaneously talk about the feedback were probed on the items listed in the questionnaire. Audio recordings were made of their vocalizations. The recording were then transcribed and analyzed to explore factors influencing their ratings.

7.2.6 Driving Task

Campus roads at Eindhoven University of Technology were used as test track for the experiment. The environment presents an urban driving scenario which allows for slow to medium speed driving. As is shown in Figure 7.5, the course starts with a slalom (indicated by placement of cones) after which a medium speed left hand turn follows. After a straight section with a course road profile an 180° turn has to be made followed by a slow speed right hand turn. Again a left hand turn is made followed by a left hand U-turn. A second left hand U-turn then has to be completed. A quick right left combination then leads to a right hand U-turn. After a left hand turn a large speed bump is taken. Two medium speed left hand turns lead back to the start point. The road surface was cobblestone, one of the common road surfaces found in the Netherlands.
Participants always begin from the Start/Stop point with the baseline condition and continue driving with the baseline till they complete the slalom. Upon completing the slalom participants receive the test condition, proceed with the medium speed left hand turn and go on to complete the driving circuit. This ensures that participants are able to compare with the baseline condition easily. A number of cornering maneuvers are included in the circuit to ensure participants are able to completely experience feedback generated by the test condition.

7.2.7 Procedure

Upon providing demographic information, participants received safety instructions, were briefed about the questionnaire, experimental protocols and underwent familiarization trials which included driving around the test track twice. During familiarization and during the experiment, the researcher was seated in the front passenger seat next to the driver to adjust the steering parameters to test conditions, record subjective experiences and administer the questionnaire.

The baseline condition was used during familiarization trials. After completion of the familiarization phase, subjects performed the driving task which included driving the slalom.
in baseline condition and the remaining task with a randomly chosen test condition. Participants were asked to think out loud while driving and were administered the questionnaire upon completion of the driving task. The events after familiarization were repeated 10 times with the different experimental condition for each participant. The order of conditions was pseudo randomized to prevent ordering effects. The dependent variables in the experimental design are subjective responses (ratings of specific experience parameters and new experience parameters that emerge during the study) and vehicle response (torque, lateral acceleration, speed, etc). The experiment took approximately 60 minutes to complete per participant.

System data in the car such as Lateral Acceleration, Steering Wheel Angle, Yaw Rate and so on were logged at the rate of 100Hz and stored for each drive.

7.3 RESULTS AND DISCUSSION

A Shapiro-Wilk test was applied on the questionnaire data to check for normality. Since the results show that there is significance at the 95% confidence interval, the data follow a non-normal distribution and hence non-parametric tests are used for further analysis of data. Since most participants expressed difficulty in understanding the term ‘Sluggishness’, ratings for the attributed were not used in data analysis.

A One-Sample Wilcoxon signed rank test with mean value of ‘0’ was applied to the subjective attribute ratings for the different test conditions to study how the subjective experiences varied as a result of changing the settings for the five different steering parameters. Results from the test for the Power Assistance Gain parameter are shown in Table 7.1

Table 7.1 Results from One-Sample Wilcoxon Signed Ranks Test for Power Assistance Gain

<table>
<thead>
<tr>
<th>Setting</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Assistance Gain (ϒ = 0)</td>
<td>Force*</td>
<td>Z = 3.407, p = .001</td>
<td>.91</td>
</tr>
<tr>
<td></td>
<td>Comfort*</td>
<td>Z = -3.401, p = .001</td>
<td>-.91</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>Z = -2.512, p = .012</td>
<td>-.67</td>
</tr>
<tr>
<td></td>
<td>Directness*</td>
<td>Z = -2.558, p = .011</td>
<td>-.68</td>
</tr>
<tr>
<td></td>
<td>Sensitivity*</td>
<td>Z = -2.157, p = .037</td>
<td>-.58</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = .879, p = .379</td>
<td>.23</td>
</tr>
<tr>
<td></td>
<td>Road Feel</td>
<td>Z = -1.483, p = .138</td>
<td>-.40</td>
</tr>
</tbody>
</table>
Results from Table 7.1 and mean ratings shown in Figure 7.6 show that when Power Assistance Gain is reduced to ‘0’ i.e., when there is no power assistance offered, the perception of force increases as expected and the ratings for other subjective attributes such as Comfort, Control, Directness and Sensitivity decrease in comparison to the baseline condition. The effect of changes to these subjective experience attributes is large ($r > 0.5$), as can be seen from Table 7.1. And when Power Assistance Gain is increased to ‘2’, maximum power assistance, the ratings for Comfort and Directness increase. It is interesting to note that while there is an increase in Comfort, there is not a significant increase in Control. The finding is different from earlier studies which showed Comfort and Control to be interdependent. This finding is interesting and shows that in a realistic driving environment participants are more sensitive to changes in subjective experience.

The findings here are in comparison with the baseline condition and hence while there is an actual increase in Control (as seen in Figure 7.6 which provides the actual ratings from the questionnaire), the increase in not significant and the effect is medium ($r < .50$). The finding also confirms earlier findings that when there are high forces, as in the case of no power assistance, there is a drop in perceived comfort and control.
Results from Table 7.2 and mean subjective ratings from Figure 7.7 for Boost Linearity show that there is a significant drop in ratings for subjective experience attributes in comparison with the baseline. With Boost Linearity at 50% there is significant drop in Force, Comfort, Control, Sensitivity, Return-to-Center Feel and Road Feel. While there are similar drops noticeable when Boost Linearity is at 100%, the drop in Comfort and Control is not significant and this shows that when the boost profile is constant drivers can adapt to the steering experience. However with an uneven boost profile, drivers are unable to gauge how the system behaves and this could have led to lower ratings when Boost Linearity is at 50%. But with overall negative ratings and strong negative effect sizes, it can be understood that adjusting the parameter may not lead to a positive subjective experience.
Table 7.2. Results from One-Sample Wilcoxon Signed Ranks Test for Boost Linearity

<table>
<thead>
<tr>
<th>Setting</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost Linearity 50%</td>
<td>Force*</td>
<td>Z = -3.33, p = .001</td>
<td>-.88</td>
</tr>
<tr>
<td></td>
<td>Comfort*</td>
<td>Z = -2.747, p = .006</td>
<td>-.73</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>Z = -2.497, p = .013</td>
<td>-.66</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>Z = -1.678, p = .093</td>
<td>-.49</td>
</tr>
<tr>
<td></td>
<td>Sensitivity*</td>
<td>Z = -3.196, p = .001</td>
<td>-.85</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = -2.347, p = .019</td>
<td>-.63</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>Z = -3.196, p = .001</td>
<td>-.85</td>
</tr>
<tr>
<td>Boost Linearity 100%</td>
<td>Force*</td>
<td>Z = -3.375, p = .001</td>
<td>-.90</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = -1.867, p = .062</td>
<td>-.50</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>Z = -1.933, p = .053</td>
<td>-.52</td>
</tr>
<tr>
<td></td>
<td>Directness*</td>
<td>Z = -2.873, p = .004</td>
<td>-.77</td>
</tr>
<tr>
<td></td>
<td>Sensitivity*</td>
<td>Z = -2.845, p = .004</td>
<td>-.76</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = -3.198, p = .001</td>
<td>-.85</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>Z = -3.028, p = .002</td>
<td>-.81</td>
</tr>
</tbody>
</table>

* Indicates significant results

Figure 7.7. Mean Subjective Ratings for Boost Linearity Test Conditions.
Results from Table 7.3 and mean ratings shown in Figure 7.8 for Torsion Bar Stiffness are on expected lines and clearly show that when Torsion Bar Stiffness is increased there is an increase in Road Feel and this is the only parameter which has a significant positive influence on Road Feel. The effect sizes are also large suggesting changes to Torsion Bar Stiffness can strongly affect the subjective experience of Road Feel. The ratings show that when Torsion Bar Stiffness is increased there is also an increase in Force. This increase brings about an interesting complexity in generating a preferred experience. Now let us suppose there is a preference for improved Road Feel. This can be offered by increasing the Torsion Bar Stiffness, but there is also increase in force which may be undesired. Hence, to negate the effect of Force and maintain it at the same level, another parameter such as Power Assistance Gain will have to be increased.

Table 7.3. Results from One-Sample Wilcoxon Signed Ranks Test for Torsion Bar Stiffness

<table>
<thead>
<tr>
<th>Setting</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion Bar Stiffness 50 Nm/rad</td>
<td>Force*</td>
<td>Z = -2.801, p = .005</td>
<td>-.75</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = 1.42, p = .887</td>
<td>.04</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>Z = -1.086, p = .277</td>
<td>-.29</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>Z = -1.084, p = .279</td>
<td>-.29</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = -1.555, p = .120</td>
<td>-.41</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = -1.492, p = .136</td>
<td>-.40</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>Z = -1.824, p = .068</td>
<td>-.49</td>
</tr>
<tr>
<td>Torsion Bar Stiffness 125 Nm/rad</td>
<td>Force*</td>
<td>Z = 3.332, p = .001</td>
<td>.89</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = .482, p = .630</td>
<td>-.13</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>Z = 1.219, p = .223</td>
<td>.32</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>Z = -.859, p = .390</td>
<td>-.22</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = -.881, p = .378</td>
<td>-.23</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = -1.980, p = .048</td>
<td>-.53</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>Z = 1.997, p = .046</td>
<td>.53</td>
</tr>
</tbody>
</table>

* Indicates significant results
Figure 7.8. Mean Subjective Ratings for Torsion Bar Stiffness Test Conditions

Results from Table 7.4 and mean ratings shown in Figure 7.9 for the Steering Wheel Damping parameter settings show that changes to the parameter to maximum and minimum values create positive ratings for the subjective experience attributes and hence better overall steering feel for the participants. Interestingly there is no improvement in Return-to-Center Feel when Steering Wheel Damping is reduced to ‘0’ as a less damped steering wheel is expected to produce a better Return-to-Center Feel. However, the findings show that increased Control and Sensitivity are perceived with a more damped steering wheel. Lack of statistical significance in subjective ratings in comparison for the two Steering Wheel Damping settings for most subjective attributes suggests that participants had a tough time in differentiating the Steering Wheel Damping settings from the baseline condition. Positive effect sizes for Comfort and Control in changing both parameters also suggests the same.
Table 7.4. Results from One-Sample Wilcoxon Signed Ranks Test for Steering Wheel Damping

<table>
<thead>
<tr>
<th>Setting</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steering Wheel Damping 0 Nms/rad</td>
<td>Force</td>
<td>Z = -.511, $p = .609$</td>
<td>-.14</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = 1.409, $p = .159$</td>
<td>.38</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>Z = 1.724, $p = .085$</td>
<td>.46</td>
</tr>
<tr>
<td></td>
<td>Directness*</td>
<td>Z = 2.112, $p = .035$</td>
<td>.56</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = 1.612, $p = .107$</td>
<td>.43</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = -.241, $p = .809$</td>
<td>-.06</td>
</tr>
<tr>
<td></td>
<td>Road Feel</td>
<td>Z = .520, $p = .596$</td>
<td>.14</td>
</tr>
<tr>
<td>Steering Wheel Damping 0.5 Nms/rad</td>
<td>Force</td>
<td>Z = 1.604, $p = .109$</td>
<td>.43</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = 1.713, $p = .087$</td>
<td>.46</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>Z = 2.167, $p = .030$</td>
<td>.58</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>Z = .850, $p = .396$</td>
<td>.23</td>
</tr>
<tr>
<td></td>
<td>Sensitivity*</td>
<td>Z = 2.157, $p = .031$</td>
<td>.58</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>Z = .431, $p = .666$</td>
<td>.11</td>
</tr>
<tr>
<td></td>
<td>Road Feel</td>
<td>Z = .791, $p = .429$</td>
<td>.21</td>
</tr>
</tbody>
</table>

* Indicates significant results

Figure 7.9. Mean Subjective Ratings for Steering Wheel Damping Test Conditions
The most surprising results were noticed for the Steering Ratio parameter where the only significant results from the One-Sample Wilcoxon Signed Rank Test was observed for the Steering Ratio 120 rad/m setting for the Return-to-Center Feel ($Z = -1.980$, $p = .048$, $r = .53$). The results were surprising because no significant effects were observed for Directness ($r < .3$ for both steering ratio settings). Figure 7.10 shows the differences in Steering Wheel Angle magnitude for both Steering Gear Ratio settings of 14 participants in comparison to their individual baseline driving performance. A value of ‘1’ on the y-axis indicates that the measures were exactly similar to their performance with the baseline condition, a value greater than ‘1’ indicates the performance observed was higher in the test condition in comparison to the baseline and a value less than ‘1’ indicates that the performance observed was lower in the test condition in comparison to the baseline. Figure 7.10 clearly shows that all 14 participants made fewer movements of the steering wheel for the Ratio 120 condition compared to the baseline condition. While the performance is as expected with drivers experiencing a more direct steering system with Steering Ratio 120 rad/m, participants surprisingly do not rate it higher on the Directness attribute in the questionnaire.

![Figure 7.10](image-url)

**Figure 7.10.** Steering Angle differences between Steering Gear Ratio settings for all 14 participants in the study.

While there are interesting results from questionnaire ratings, it would be interesting to see if performance was affected by changes to steering parameters. Performance was measured
by means of observing the cornering speeds as measured by yaw rate sensors in the SbW test vehicle. Since it is known that drivers may reduce speed in uncertain/unsafe situations, it was decided to check if drivers made such compensations while cornering with steering settings that they are not used to. Additionally if drivers lower or increase cornering speed it is bound to affect their steering angle deviation and steering speed and hence yaw rate gives a comprehensive picture of performance. Now it is possible that different drivers have different driving styles and this could affect performance measures. To prevent such confounding, performance was studied individually for each participant by comparing performance in test conditions to their own performance with baseline condition. Hence in Figures 7.11, 7.12, 7.13, 7.14 and 7.15 which show performance with the test conditions, the y-axis indicates the standard deviation gradient i.e., standard deviations in yaw rate in the test condition divided by standard deviation in yaw rate in the baseline condition.

![Power Assistance - Yaw Rate](image)

**Figure 7.11. Yaw Rate comparisons for Power Assistance**
Figure 7.12. Yaw Rate comparisons for Boost Linearity

Figure 7.13. Yaw Rate comparisons for Torsion Bar Stiffness
Figure 7.14. Yaw Rate comparisons for Steering Wheel Damping

Figure 7.15. Yaw Rate comparisons for Steering Ratio
Figures 7.11-7.15 show that participants were able to adapt to the different steering parameter settings as is evident from the red and black lines having a similar pattern and overlapping each other. Also it can be seen that participants 5, 6 and 7 had difficulty in maintaining performance similar to their baseline driving performance, whereas other participants were able to quickly adapt. The findings add validity to earlier conducted simulator studies (Anand, Terken & Hogema, 2013), which showed that participants were able to adapt performance easily. Here again, participants were able to adapt to extremely high feedback torque conditions such as Power Assistance Gain 0 and extremely light feedback torque conditions such as Boost Linearity 100%.

Having analyzed the questionnaire data and the performance as captured in the system logs, it is interesting to see if the think-out-loud sessions while driving contribute additional information regarding subjective experiences with the different test conditions. Content analysis of the transcriptions reveals that the questionnaire is able to capture all experiences that subjects relate to steering feel. The most interesting information the audio recordings provide are about participant preference for a particular steering feel even though participants were not asked explicitly about it as that was not the aim or objective of the study. The transcriptions indicate that the overall judgment or preference to a setting is arrived at by first assessing the feel with Comfort, Control and Safety, which emerge as high order control variable in assessment of steering feel. There are also other variables such as Steering Maneuver, Road Condition, Traffic Condition and so on which emerge as modulating variables in deciding what attributes of steering feel are required the most for a given situation. In studying the audio transcriptions along with findings from the questionnaire, the picture as shown in Figure 7.16 emerges regarding the mapping between the physical parameters of steering feel and the subjective experience attributes relating to steering feel.
Figure 7.16 however does not provide a specific mapping between the parameters in the physical space and attributes in the subjective space. Based on the analyses of questionnaire data presented and discussed earlier and also audio transcriptions, the mapping is now made for individual parameters.

For the Power Assistance Gain parameter, from Table 7.1, it can alter the experience of Force, Comfort, Control, Directness and Sensitivity. Based on Figure 7.16, it can be concluded that Power Assistance Gain varies the subjective experience of Force, Directness and Sensitivity and these can be varied to different levels based on preference to offer Comfort, Control and Safety. From Table 7.1, it is clear that generally high levels of Force and lower levels of Directness and Sensitivity with no power assistance contribute to reduced comfort and control.

Similarly for Boost Linearity parameter, from Table 7.2, it is can be said that it can change the subjective experience Force, Directness, Comfort, Control, Sensitivity, Return-to-Center Feel and Road Feel significantly different from the baseline. Therefore, based on Figure 7.16, it can be concluded that Boost Linearity varies the subjective experience of Force, Sensitivity,
Return-to-Center Feel and Road feel and these can be altered to desired level of Comfort, Control and Safety. From, Table 7.2 it is clear that increasing Boost Linearity leads to lowering Force, Directness, Sensitivity, Return-to-Center Feel and Road feel and in general lower levels of Comfort and Control.

For the Torsion Bar Stiffness parameter, from Table 7.3, it can be said that when the parameter values are increased, there is an increase in experience of Force, Return-to-Center Feel and Road Feel. Based on Figure 7.16, it can be concluded that Torsion Bar Stiffness varies the experience of Force, Return-to-Center Feel and Road Feel and these may be varied based on drivers’ desired Comfort, Control and Safety.

For the Steering Wheel Damping parameter, from Table 7.4, it can be said that the parameter can vary the experience of Directness, Control and Sensitivity. Based on Figure 7.16, it can be concluded that Steering Wheel Damping can vary the experience of Directness and Sensitivity and these can be modified depending on desired level of Comfort, Control and Safety. It is found that increasing the Steering Wheel Damping increases Control for the test-participants.

For the Steering Gear Ratio parameter it is found from questionnaire analysis that it can vary the Return-to-Center Feel but the steering wheel angle data plots in Figure 7.10 show that system directness is also changed. Therefore if the parameter is varied at much higher levels from the baseline than what was done in the study, it likely to alter the experience of Directness. Based on this discussion and from Figure 7.16, it can be concluded that Steering Gear Ratio can alter the experience of Return-to-Center Feel and Directness and these can be varied according to desired level of Comfort, Control and Safety.

It must be noted that the preference and attributes in the subjective space for all the parameters changes are modulated by modulating variables as shown in Figure 7.16. Based on results and the discussion above, the mapping between the five steering parameters and subjective experience attributes is as shown in Table 7.5.
Table 7.5. Mapping between the five steering parameters and subjective experience attributes.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Subjective Experience Attributes</th>
<th>Higher Order Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force</td>
<td>Directness</td>
</tr>
<tr>
<td>Power Assistance Gain</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Boost Linearity</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Torsion Bar Stiffness</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Steering Wheel Damping</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Steering Gear Ratio</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

x – Indicates Significant Influence from Baseline

7.4 CONCLUSION

The study was successful in exploring the relationship the subjective experiences relating to steering feel and mapping the physical steering parameters with subjective experience parameters.

Similar to earlier studies, this study also finds that performance is not affected by changing the steering settings. However, the experiment did not include high speed driving tasks and it is possible that at slow speeds participants are able to easily adapt to the different steering settings. It may be interesting to see if not just performance but also subjective ratings and opinions remain same at higher speeds.

In conclusion, the study finds that specific elements of steering feel can be modified to suit individual or personal preferences by adjusting the steering system parameters to different values. While it is clear as to which steering parameter is to be modified to change experience at low speeds, it would be interesting to see if the same holds for high speeds.
CHAPTER 8

Mapping Physical Steering Parameters to Subjective Experience Attributes

Part II
8.1 INTRODUCTION

The study presented in this chapter is a follow-up to the study discussed in Chapter 7. The previous study was able to successfully explore and map the relationship between physical steering parameters and subjective experience attributes. It was also found in the previous study that drivers were able to quickly adapt to different steering settings while maintaining similar levels of driving performance. Even settings which were rated poorly by drivers did not affect their performance significantly. However, it must be reminded here that the earlier study was undertaken at relatively low speeds i.e., in the 25-30 kmph speed range. The question then arises as to whether performance can be maintained for different settings in high speed driving scenarios where the steering wheel input has greater effect on vehicle stability and personal safety. Apart from performance, it also remains to be seen if the mapping between physical steering parameters and subjective experience attributes are the same at higher speeds. At high speeds there are smaller movements of the steering wheel and hence the subjective experiences could differ and there may be additional needs for the driver. And driving at higher speeds also has a greater impact of safety. Due to these reasons, the follow-up study presented in this chapter is required.

Earlier studies discussed in Chapter 5 and Chapter 6 did show that participants were capable of adjusting to different levels of feedback torque in a driving simulator even while being occupied with a secondary task. Participant feedback from the simulator studies pointed out that safety did not influence their performance as they were driving on simulated roads where the consequence of poor performance is unlikely to have an effect on personal safety. However, in a realistic environment such as that of driving the prototype test vehicle in a test track, performance has a direct relationship to personal safety. On the premise that safety may affect driving performance, the following hypotheses are formulated for this study which uses the same experimental settings as the previous experiment.

It is hypothesized that drivers will alter their driving speeds with settings based on their ratings for various subjective attributes of steering feel. In particular, it is expected that drivers are likely to drive slower in settings rated negatively and faster with settings that are rated positively. Hence with settings such as Power Assistance Gain $\Upsilon = 2$, Boost Linearity 50% and Boost Linearity 100% which were also offered in the previous study, drivers are expected to drive much slower as these settings were rated poorly. In the previous study subjective Control was also rated poorly and since this is critical in handling a vehicle, it is expected to make drivers reduce their driving speed. While speed reduction is expected for settings rated poorly, participants are likely to drive at higher speeds with settings that were rated positively.
Since the previous study did not study lane keeping performance due to lack of a capable equipment and also a test track which did not have lane marking, it made it difficult to judge performance within a lane. Hence for this study, a lane position sensor was leased and installed on the prototype vehicle. The sensor was capable of detecting lateral deviations within the lane by recording the position of the vehicle in reference to the solid white marking on the asphalt surface which marks the edge of the road. However, unexpectedly the sensor failed midway through the experiment and the failure was only detected on completion of the experiment. Therefore lane keeping performance could not be properly studied.

The subjective experience is again measured using a questionnaire containing the same attributes used in the earlier study with minor changes as described in the methods section. It is hypothesized that the subjective experiences will not differ from those observed in the earlier study since the same experimental settings are repeated again. Since many participants in the previous study alluded to Safety as an important attribute which influenced their overall judgment of a setting, it was decided to study ratings for subjective experience of Safety as well in this study. It is therefore hypothesized that Safety ratings are also likely to have a direct relationship to overall ratings for steering feel and driving speed.

In replicating the test settings of Chapter 7, while at the same time conducting a similar study at higher speeds, the findings will indicate whether the hypotheses are to be rejected or retained. In a scenario where the hypotheses are retained, it will suggest that drivers are not capable of adapting to all types of steering settings as earlier observed and more specifically, performance is likely to be poor for settings that are rated poorly for Safety. Such a finding would mean that driver capabilities of handling settings which offer extreme (low and high) levels of feedback torque need to be examined more carefully prior to offering settings for personalization. Such a finding would also contradict with earlier findings from simulator studies which showed that drivers can easily adapt to different levels of feedback torque easily. Contradicting result may negatively impact external validity of driving simulators for these types of studies.

If the findings provide basis to reject the hypotheses then it would suggest that drivers can adapt to different steering settings easily and deliver good performance with different kinds of settings. The findings would further validate the findings from earlier simulator studies discussed in Chapter 5 and Chapter 6. In addition, the findings would suggest that driving performance with settings preferred by a driver would not require additional scrutiny except in cases of extreme driving conditions which have not been tested in this thesis.
8.2 Method

8.2.1 Experimental Design

The study conducted followed a within-subjects design wherein all subjects were exposed to the same set of experimental settings. As the current study is a follow-up to the previous study, the same set of experimental settings used in the study discussed in Chapter 7 is retained. For quick reference, the test settings are shown in Figure 8.1.

![Parameter Settings Diagram](image)

Figure 8.1. Experimental Settings.

Participants were exposed to all the test settings listed in Figure 8.1 and also the baseline setting, where all parameters are maintained at the default setting for operation of the test-vehicle in Steer-by-Wire (SbW) mode. The experiment started always with the baseline setting followed by the 10 test settings in which each parameter was varied to a test setting shown Figure 8.1. Only one parameter was varied in each setting while all other parameters were maintained at their default values. The order of the 10 settings was randomized and offered to participants to prevent ordering effects. After driving with each setting, participants rated the subjective experience attributes with the questionnaire. Ratings were
also recorded this time for the baseline setting. After the 10 randomized settings, the baseline setting was offered again to participants to study whether they were able to reproduce similar ratings for the baseline setting after receiving the test settings. Participants were not informed that the final setting was the baseline setting. Similar ratings for the baseline settings would suggest that the ratings from participants are reliable and that participants are highly sensitive to feedback changes on the steering wheel.

Apart from introducing the baseline condition twice, another change implemented in the current study was that the subjective experiences were rated individually for each test setting as opposed to a comparison rating (to the baseline) as was done in the previous study. Several participants in the earlier study mentioned that it required high levels of concentration to compare the test setting against the baseline setting on 9 different attributes listed in the questionnaire. Taking participants’ views into consideration, it was decided to allow participants to rate the subjective experience attribute individually. As a consequence, a slalom course with baseline setting was not needed. On the other hand, with the elimination of the baseline comparison, it is likely that subjective experience could be influenced by the previous test setting. For instance, if a subject drives in a setting with extremely high feedback torque and then continues to drive in a setting with a moderate feedback torque setting, it is likely that the moderate feedback torque setting may receive very low ratings in experience of Force as the change experience of Force is of a high magnitude. And these ratings may be influenced by order of the settings. To prevent such extreme effects and neutralize subjects experience levels, prior to each test setting, participants were required to make a short drive and complete a 360 degree turn with the baseline setting.

8.2.2 Equipment

The BMW prototype SbW vehicle used in Chapter 7 was again used as the test platform. Since the same vehicle was used in the earlier study please refer to the section 2.2 in Chapter 7 to read about the Steering System Dynamics, Steering Model and Parameter Selection.

8.2.3 Questionnaire

The questionnaire used in the current study recorded ratings for subjective attributes of steering feel. The questionnaire was however slightly modified to suit the changes made to the experimental design and opinions expressed by participants from the previous study. The questionnaire (as seen in Appendix B.3) retained the following 7 attributes from the earlier study namely Force, Comfort, Control, Sensitivity, Return-to-Center Feel, Directness and Road Feel. Sluggishness, an attribute used to also capture the return-to-center feel, was removed from the questionnaire since participants were unable to relate to the term and
were confused about its meaning even after explanations. Safety was an attribute that was included in the questionnaire as it was found to be a subjective element altered by steering feedback from the previous study. Ratings for Overall Steering Feel were also captured using this questionnaire. Hence in the questionnaire used to assess steering feel, there were 8 attributes (Force, Comfort, Safety, Control, Directness, Return-to-Center, Sensitivity and Road Feel) that were rated and also participants rated Overall Steering Feel. Since the current study does not make comparison ratings against baseline, a seven point Likert scale ranging from 1 – Low to 7 – High was used to rate subjective experience attributes for the different test settings individually. Since the scale ranges from Low to High, a score of 4 would not indicate ‘no change’ but instead mean that the experience was ‘moderate’.

8.2.4 Participants

12 participants who were students and employees of Eindhoven University of Technology and who were regular drivers of a passenger car for a minimum period of 2 years were recruited for the study. Of the 12 participants, 9 were male and 3 were female subjects. Mean age of the 12 participants was 29.5 years (SD = 6.7). Mean driving experience of all the participants was 8.7 years (SD = 4.8). Among the 12 participants, three had annual driving mileage of less than 2000 km, four had annual driving mileage between 2000 km and 5000 km and five had annual driving mileage greater than 5000 km.

8.2.5 Driving Task

Test-tracks at the Generaal Majoor de Ruyter van Steveninck Dutch army barracks located at Eindhovensedijk 42, 5688 GN Oirschot were used to form the driving circuit for the experiment. The driving circuit is as shown in Figure 8.2. The driving circuit was 2.5 km long. The road surface in this study was a tar-surface similar to those found in highways around the world. The road surface is different from the cobblestone road surface used in the previous study.
Starting from point A, participants proceeded to take a 90 degree left turn and drive at high speeds along the straight stretch. At the end of the straight stretch participants took a gradual left turn and proceeded to go around the roundabout following which they would proceed to the weaving lane where they were required to make alternating left and right turns i.e., weaving. Participants would then return to point A and bring the vehicle to a stop. Prior to receiving the different test settings participants would have to make a 360 degree turn from position A and return to the same point with the baseline setting.

8.2.6 Procedure

Participants were briefed about the experiment and were first driven around the test circuit by the researcher. Participants were then allowed to familiarize themselves with the test vehicle and the driving circuit by letting them drive around the circuit twice. During familiarization participants were exposed to different test settings (including those that offered low and high feedback torque) briefly to allow them to get a feel for the different steering feedback conditions they were going to encounter during the experiment. Exposure to the test settings was done as a safety precaution such that the participant is prepared to
handle extremely heavy or light settings that they encountered while performing the driving task. Once familiarization was complete, participants proceeded to make a 360 degree turn at point A (shown in Figure 8.2) and continued to drive the circuit with the baseline setting first. After completing the circuit, participants were required to rate the subjective experience attributes of steering feel on the questionnaire. Once ratings were obtained, participants made the 360 degree turn at the starting point with the baseline setting and continued to drive along the circuit with a randomly chosen test setting (a settings that a participant had not yet received) from Figure 8.1. After completing the driving circuit, the questionnaire was again administered. The same protocol was applied until each participant received all the 10 experimental settings. After receiving the 10 settings, participants were again offered the baseline setting to check for reliability in their ratings. Data from the 12 drives (10 drives with 10 experimental settings and 2 drives with baseline setting) were recorded in Matlab Simulink via the dSpace control box. System recorded data included driving speed, lateral acceleration, yaw rate and steering wheel angle. Data were recorded at the rate of 100 Hz.

8.3 RESULTS AND DISCUSSION
In the previous study subjective experiences of test settings were compared to the baseline and measured using a dissimilarity scale. In the current study subjective experiences were measured for the test settings individually and separate measures were also recorded for the baseline, which was offered twice – as the first test setting and the final test setting. The reliability of participant ratings was observed by performing paired sample Wilcoxon Signed Rank Tests between ratings for subjective attributes for both baseline conditions. Results revealed that the differences in ratings were insignificant and thereby show that participants can accurately rely on their senses to notice changes in steering system characteristics and provide ratings for the subjective experience attributes. The mean subjective ratings across participants are as shown in Figure 8.3.
To compare the results in this study to the previous study, ratings for subjective experience attributes are compared to the baseline setting. Since there is no significant difference observed between the two baseline settings, the average of the two is taken for comparison against other test settings. Henceforth, baseline ratings refer to mean ratings from both the baseline conditions. Paired samples Wilcoxon Signed Rank Tests were conducted between the baseline ratings and ratings for subjective experience attributes with each of the test conditions.

Results from the Wilcoxon Signed Rank Tests for the Power Assistance Gain parameter are shown in Table 8.1. The differences in mean ratings between the Power Assistance Gain settings and the baseline setting are shown in Figure 8.4. It must be noted that the mean differences were computed to only illustrate differences in ratings between the different settings to the baseline. The original ratings on the 7-point scale were used for the Paired samples Wilcoxon Signed Rank Tests. As seen from Table 8.1 and figure 8.4, when Power Assistance Gain is reduced to ‘0’ i.e., when there is no power assistance offered, the perception of force increases as expected and the ratings for other subjective attributes such as Road Feel, Sensitivity, Control, Comfort and Safety significantly decrease. The large effect sizes are reinforces the same. The finding confirms results from earlier studies which showed that increasing the level of feedback torque to high levels decreases perceived comfort and control. The Overall Steering Feel is also rated significantly lower than the baseline when there is no power assistance. On the other hand, Table 8.1 and Figure 8.4 show that
increasing the Power Assistance Gain does not alter the subjective experiences significantly from the baseline. Figure 8.4 shows that the ratings for high assistance are almost similar to those for the baseline.

Table 8.1. Results from the Wilcoxon Signed Ranks Test for Power Assistance Gain

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Assistance Gain ((Y = 0))</td>
<td>Force*</td>
<td>(Z = -3.007, p = .003)</td>
<td>-.86</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>(Z = -2.184, p = .029)</td>
<td>-.63</td>
</tr>
<tr>
<td></td>
<td>Sensitivity*</td>
<td>(Z = -2.518, p = .012)</td>
<td>-.73</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>(Z = -1.735, p = .083)</td>
<td>-.50</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>(Z = .00, p = 1.0)</td>
<td>.00</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>(Z = -3.066, p = .002)</td>
<td>-.88</td>
</tr>
<tr>
<td></td>
<td>Comfort*</td>
<td>(Z = -2.870, p = .004)</td>
<td>-.82</td>
</tr>
<tr>
<td></td>
<td>Safety*</td>
<td>(Z = -2.855, p = .004)</td>
<td>-.82</td>
</tr>
<tr>
<td></td>
<td>Overall Steering Feel*</td>
<td>(Z = -2.955, p = .003)</td>
<td>-.85</td>
</tr>
<tr>
<td></td>
<td>(\text{Power Assistance Gain ((Y = 2))})</td>
<td>Force</td>
<td>(Z = -1.213, p = .225)</td>
</tr>
<tr>
<td></td>
<td>Road Feel</td>
<td>(Z = 1.336, p = .182)</td>
<td>.38</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>(Z = -.462, p = .644)</td>
<td>-.13</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>(Z = -.514, p = .607)</td>
<td>-.14</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center</td>
<td>(Z = -.269, p = .788)</td>
<td>-.07</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>(Z = -1.081, p = .280)</td>
<td>-.31</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>(Z = -.781, p = .435)</td>
<td>-.22</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td>(Z = -.310, p = .756)</td>
<td>-.09</td>
</tr>
<tr>
<td></td>
<td>Overall Steering Feel</td>
<td>(Z = -.635, p = .526)</td>
<td>-.18</td>
</tr>
</tbody>
</table>

* Indicates significant results
Figure 8.4. Mean Difference Ratings for Power Assistance Gain Test Conditions

Table 8.2. Results from the Wilcoxon Signed Ranks Test for Boost Linearity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boost 50%</td>
<td>Force*</td>
<td>Z = -2.943, p = .003</td>
<td>-.85</td>
</tr>
<tr>
<td></td>
<td>Road Feel</td>
<td>Z = -1.277, p = .201</td>
<td>-.37</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = -.314, p = .754</td>
<td>-.09</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center*</td>
<td>Z = -2.185, p = .029</td>
<td>-.63</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>Z = -1.203, p = .229</td>
<td>-.35</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>Z = -2.374, p = .018</td>
<td>-.68</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = -1.755, p = .079</td>
<td>-.51</td>
</tr>
<tr>
<td></td>
<td>Safety*</td>
<td>Z = -2.640, p = .008</td>
<td>-.76</td>
</tr>
<tr>
<td>Boost 100%</td>
<td>Force*</td>
<td>Z = -3.075, p = .002</td>
<td>-.89</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>Z = -3.068, p = .002</td>
<td>-.88</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = -1.653, p = .098</td>
<td>-.48</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center*</td>
<td>Z = -2.988, p = .003</td>
<td>-.80</td>
</tr>
<tr>
<td></td>
<td>Directness*</td>
<td>Z = -2.364, p = .018</td>
<td>-.68</td>
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<tr>
<td></td>
<td>Control*</td>
<td>Z = -2.548, p = .011</td>
<td>-.73</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = -1.797, p = .072</td>
<td>-.52</td>
</tr>
<tr>
<td></td>
<td>Safety*</td>
<td>Z = -2.848, p = .004</td>
<td>-.82</td>
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<tr>
<td></td>
<td>Overall Steering Feel</td>
<td>Z = -3.065, p = .002</td>
<td>-.88</td>
</tr>
</tbody>
</table>

* Indicates significant results
Significant results from the Wilcoxon Signed Rank Test for the Boost Linearity parameter are shown in Table 8.2. The differences in mean ratings between the Boost Linearity settings and the baseline setting are shown in Figure 8.5. As seen from Figure 8.5, when Boost Linearity is increased to 50%, there is an overall drop in ratings for subjective experience attributes compared to the baseline. Significant differences are noted for Force, Return-to-Center, Control and safety as shown in Table 8.2. The Overall Steering Feel also reduces. Table 8.2 and Figure 8.5 show that when Boost Linearity is increased to its maximum value of 100%, there are significant decreases in perception of Force, Return-to-Center, Control and Safety compared to the baseline condition. These results are also found when Boost Linearity is increased to 50%. However, from Figure 8.5 it can be seen that the ratings are much lower when Boost Linearity is increased to 100%. Additionally, there is also reduced perception of Road Feel and Directness when Boost Linearity is increased to 100%. The poor ratings confirm earlier findings that when there is extremely low feedback torque, as in the case of Boost Linearity 100%, there is significant drop in perceived Control. Though the test results find no significant differences in Comfort ratings, it can be seen from effect sizes that there is large negative effect on the experience of Comfort when Boost Linearity is increased to 50% and beyond. The findings further help reinforce that Comfort in the context of steering does not entirely depend on the physical effort.

![Figure 8.5. Mean Difference Ratings for Boost Linearity Test Conditions](image-url)
Results from the Wilcoxon Signed Rank Tests for the Torsion Bar Stiffness parameter are shown in Table 8.3. The differences in mean ratings between the Boost Linearity settings and the baseline setting are shown in Figure 8.6.

### Table 8.3. Results from the Wilcoxon Signed Ranks Test for Torsion Bar Stiffness

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subjective Attributes</th>
<th>Z Scores</th>
<th>Effect Size r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion Bar Stiffness Nm/rad</td>
<td>Force*</td>
<td>Z = -2.829, p = .005</td>
<td>-.82</td>
</tr>
<tr>
<td></td>
<td>Road Feel</td>
<td>Z = -1.608, p = .108</td>
<td>-.46</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = -0.237, p = .813</td>
<td>-.07</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center*</td>
<td>Z = -1.384, p = .166</td>
<td>-.63</td>
</tr>
<tr>
<td></td>
<td>Directness</td>
<td>Z = -1.263, p = .207</td>
<td>-.36</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>Z = -2.374, p = .018</td>
<td>-.68</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = -0.672, p = .502</td>
<td>-.19</td>
</tr>
<tr>
<td></td>
<td>Safety*</td>
<td>Z = -2.640, p = .008</td>
<td>-.76</td>
</tr>
<tr>
<td></td>
<td>Overall Steering Feel*</td>
<td>Z = -2.957, p = .003</td>
<td>-.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torsion Bar Stiffness Nm/rad</td>
<td>Force*</td>
<td>Z = -2.823, p = .005</td>
<td>-.81</td>
</tr>
<tr>
<td></td>
<td>Road Feel*</td>
<td>Z = -3.068, p = .002</td>
<td>-.88</td>
</tr>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Z = -0.718, p = .472</td>
<td>-.21</td>
</tr>
<tr>
<td></td>
<td>Return-to-Center*</td>
<td>Z = -2.988, p = .003</td>
<td>-.80</td>
</tr>
<tr>
<td></td>
<td>Directness*</td>
<td>Z = -2.364, p = .018</td>
<td>-.68</td>
</tr>
<tr>
<td></td>
<td>Control*</td>
<td>Z = -2.548, p = .011</td>
<td>-.73</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Z = -1.742, p = .082</td>
<td>-.50</td>
</tr>
<tr>
<td></td>
<td>Safety*</td>
<td>Z = -2.848, p = .004</td>
<td>-.82</td>
</tr>
<tr>
<td></td>
<td>Overall Steering Feel</td>
<td>Z = -3.065, p = .002</td>
<td>-.88</td>
</tr>
</tbody>
</table>

* Indicates significant results

As can be seen from Table 8.3 and Figure 8.6, changes to Torsion Bar Stiffness affect Force but do not affect ratings for Road Feel unlike the previous study. The finding indicates that changes to Road Feel are perceived primarily at lower speeds and/or on uneven road surfaces such as the cobblestone surface in the previous study. Figure 8.6 shows that increasing Torsion Bar Stiffness decreases ratings for Comfort although the difference is not significant.
And as was the case in the earlier study, changes to Steering Wheel Damping and Steering Gear Ratio did not have a significant effect on ratings for subjective attributes based on results from the Wilcoxon Signed Rank Tests. The means difference ratings from baseline in the test conditions for Steering Wheel Damping and Steering Gear Ratio are shown in Figure 8.7 and 8.8, respectively. The figure shows that the test conditions offer experiences very similar to the baseline which indicates high level of Control and moderate experience of other subjective experience attributes as seen in Figure 8.3.
Figure 8.7. Mean Difference Ratings of Subjective Attributes for Steering Wheel Damping Settings

Figure 8.8. Mean Difference Ratings of Subjective Attributes for Steering Gear Ratio Settings
Apart from these items in the questionnaire, most participants also talked about on-center feel while driving. Since the driving circuit involved straight line driving at speeds of up to 80 km/hr, participants felt the need to describe how the steering wheel must feel when driving on-center where only small corrections need to be made on the steering wheel. Most participants mentioned that the steering wheel must have a clearly defined center point where the driver can be assured that he is holding the steering wheel at the center point. Furthermore, participants mentioned that it is important that the system recognizes the driver is driving at high speeds and accordingly increases feedback torque to give them a sense of increased control.

Based on participant opinions of settings that were offered, it again emerged that Comfort, Control and Safety are the higher-order variables that must be taken into account by customizable settings and that preferences are modulated by modulating variables. The general mapping therefore remains the same as shown in Figure 7.16 in the previous chapter. However, with the individual parameters there are some changes observed.

As seen in Table 8.1 and Figure 8.4, the Power Assistance Gain parameter can be used to vary the experience of Force, Road Feel and Sensitivity. The lack of power assistance (Power Assistance Gain 0), can adversely affect Comfort, Control, Safety and Overall Steering Feel as seen with ratings from Figure 8.4. These are similar to findings discussed in Chapter 7, in which the settings were offered a relatively lower driving speed. But at lower speeds, Power Assistance Gain also varies the experience of Directness which was not observed at higher speeds.

From Table 8.2, it can be seen that the Boost Linearity parameter can be used to vary the experience of Force, Road Feel, Return-to-Center Feel and Directness. Studying the subjective ratings for Boost Linearity settings in Figure 8.5, it is clear that increasing Boost Linearity results in poor ratings of higher order variables (Comfort, Control and Safety) and also decreases the Overall Steering Feel. At lower speeds, Boost Linearity also affects the subjective experience of Sensitivity in addition to the subjective experience attributes mentioned above.

The Torsion Bar Stiffness Parameter, from Table 8.3, only varies the subjective experience of Force. This is different from the mapping observed at lower speeds, where it also affected the experience of Return-to-Center Feel and Road Feel.

At higher speeds, the Steering Wheel Damping Parameter and Steering Gear Ratio parameter did not alter any subjective experience. Whereas at lower speeds, as in the previous study, Steering Wheel Damping was found to vary the subjective experience of Directness and Sensitivity; and Steering Gear Ratio varied the experience of Return-to-Center Feel and Directness.
The aim of the study was to map physical parameters changes to subjective experience attributes at higher speeds and study whether the mapping is different from that observed at lower speeds. To study the differences in mapping between physical parameters and subjective experience attributes at low and high speeds, an overview of the results is shown in Table 8.4. The table does not include the higher-order variable Safety and subjective experience ratings for Overall Steering Feel as they were not measured at in the previous study conducted lower speeds.

**Table 8.4. Mapping between Physical Steering Parameters and Subjective Experience Attributes at Low Speeds and High Speeds**

<table>
<thead>
<tr>
<th>LOW SPEEDS</th>
<th>Subjective Experience Attributes</th>
<th>Higher Order Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Force</td>
<td>Road Feel</td>
</tr>
<tr>
<td>Power Assistance Gain</td>
<td>0</td>
<td>(+)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>(-)</td>
</tr>
<tr>
<td>Boost Linearity</td>
<td>50%</td>
<td>(-)</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>(-)</td>
</tr>
<tr>
<td>Torsion Bar Stiffness</td>
<td>50 N</td>
<td>(-)</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>(+)</td>
</tr>
<tr>
<td>Steering Wheel Damping</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Steering Gear Ratio</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HIGH SPEEDS</th>
<th>Subjective Experience Attributes</th>
<th>Higher Order Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Force</td>
<td>Road Feel</td>
</tr>
<tr>
<td>Power Assistance Gain</td>
<td>0</td>
<td>(+)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Boost Linearity</td>
<td>50%</td>
<td>(-)</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>(-)</td>
</tr>
<tr>
<td>Torsion Bar Stiffness</td>
<td>50</td>
<td>(+)</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>(-)</td>
</tr>
<tr>
<td>Steering Wheel Damping</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Steering Gear Ratio</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160</td>
<td></td>
</tr>
</tbody>
</table>

* Indicates Significant Influence, + Indicates Increase, - Indicates Decrease
The mappings between physical parameters and subjective experience attributes at higher speeds are somewhat different than those observed at lower speeds. The subjective experience appears subdued at higher speeds suggesting that drivers are more sensitive to steering parameter changes at lower speeds. From table 8.4 it is clear that drivers are more aware of Road Feel, Sensitivity and Directness. Differences in Road Feel between the previous and current study may be attributed to the fact the road surface in the current study was conducted at higher speeds, was smooth (tar coated surface), which is significantly different from the cobblestone surface used in the previous experiment. The remaining changes in mapping may be due to the effect of speed and larger steering wheel movements at lower speeds. Methodological changes in studying the mapping may also have had an effect. In the previous study, comparison ratings were made directly against the baseline whereas in this study, the comparison ratings to the baseline were derived from differences in ratings between the different test conditions and baseline condition. The circuit also did not involve large steering maneuvers as done in the previous study.

With regard to performance, a one way analysis of variance was conducted on the mean driving speeds recorded in the 10 different test settings and also the first baseline setting. The second baseline setting was not included due to data inconsistencies for one participant. Results show that the test settings did not have a significant effect on driving speed ($F(10, 64.61) = 1.41; p = .18$) thereby rejecting the hypothesis that drivers will make speed adjustment in settings which receive poor ratings for Safety. The findings instead reaffirm earlier findings from Chapter 4 and Chapter 5 which show that drivers can adapt to different steering settings including extremely heavy and light settings.

It is possible that drivers only change their cornering speeds to adapt to the different settings and to see if that was the case, a one way analysis of variance was conducted on mean lateral acceleration data computed for the 10 different test settings and the first baseline setting. Results again show that the test settings did not have an effect ($F(10, 121) = 1.38, p = .19$) on lateral acceleration, suggesting that overall the cornering speeds were similar irrespective of the steering settings. This again shows that drivers are able to adapt to steering settings easily.

The performance results therefore comprehensively reject the hypothesis that drivers will alter their driving performance if the steering wheel feedback is rated poorly with respect to perceived Safety.

8.4 CONCLUSION AND GENERAL DISCUSSION

The study validates the relationship between physical parameter changes and subjective experience attributes found in the earlier study and finds that the general mapping between the physical space (defined by the model) and the subjective space is similar at different
speed levels. The mapping however, shows that changes in Road Surface and higher driving speeds affect the subjective experience. The study again finds that Force is a dominant effect of steering feel which can influence ratings for other subjective attributes. However, there are other elements of steering feel which can be altered by changing parameters such as Steering Ratio, Damping and Torsion Bar Stiffness within moderate ranges of feedback torque. The study was able to definitely prove that the ratings from participants are reliable which is shown by consistently similar ratings for the baseline setting. The lack of significant effect of the test settings on driving speed and lateral acceleration force suggests that drivers are highly capable to adapt to different steering settings. Ability to adapt to different steering settings again confirms findings from previous studies conducted in the Green Dino driving simulator and this adds external validity to the studies discussed in Chapter 3, 5, and 6.

The studies in this and the previous chapter also explored the subjective experience attributes that contribute to the experience of steering feel. While there may be individual differences in preferences for steering feel, it can be said from the study that steering feel is a subjective experience defined by a driver’s perception of Force, Return-to-Center Feel, On-Center Feel, Directness, Road Feel and Sensitivity that the steering wheel offers which in turn influence a driver’s feeling of Comfort, Control and Safety.

For future research it needs to be studied how the relationship between physical parameters and subjective experience changes when multiple parameters are changed simultaneously. Also performance under more extreme driving conditions such as poor road surfaces, high speed collision avoidance and high speed lane change tests should be studied to gather requirements for defining the design space of SbW systems.
CHAPTER 9
CONCLUSIONS
This chapter begins by re-highlighting the significance of Steer-by-Wire (Sbw) systems in today’s world. This chapter will then revisit the research challenges of this thesis and will address them individually in section 9.2 by presenting a summary of conclusions and contributions from the five research studies presented in Chapters 3, 5, 6, 7 and 8. The limitations of our research will then be presented in section 9.3. As mentioned in the introduction of this thesis, one of the research aims was to present system requirements for SbW development and also recommendations for an HMI design on which drivers can make their choices. They are presented in sections 9.4 and 9.5, respectively. Final thoughts on research and directions for future work are presented in section 9.6.

9.1 INTRODUCTION

Innovations in the automotive industry continue to emerge at a rapid pace with technological advancements. The innovations play a pivotal role in keeping the automotive industry in sync with emergence of technology in other spheres of life. Innovations further ensure that the driver is presented with new opportunities to enhance his/her experience in driving a passenger vehicle. By-wire systems are one such innovation that provides new opportunities for the driver. By-wire systems in vehicles also mark a generational shift in vehicle architecture and design from reliance on mechanical component assembly to integrated computerized electromechanical sub-systems operating over a communication network. The system offers enhanced safety, vehicle efficiency, optimal sub-system performance and design flexibility to integrate Advanced Driver Assist Systems (ADAS). The development of by-wire technology is a necessity in the context of the growing need to optimize vehicle sub-systems for fuel efficiency, emissions and more importantly to offer new and exciting experiences for the driver to make the cars marketable.

A Steer-by-Wire (SbW) system, an important sub-system of a by-wire vehicle, is used for controlling the lateral position of the vehicle. With SbW systems, as has been explained in this thesis, there is loss of the inherent feedback associated with mechanical steering systems and hence there is a challenge to generate feedback that feels natural. The natural feedback needs to be generated by developing a steering algorithm and programming the electromechanical actuators to provide feedback which would have been naturally transmitted with other systems. Now, considering the developments that have taken place with steering systems and the introduction of power assistance, the very definition of natural feedback can be re-defined. And, car manufacturers only provide drivers with a single setting or a set of options with labels such as Relaxed, Normal or Sporty, which may be perceived differently by different individuals. With several modifications being made,
‘natural’ might vary based on one’s own experiences, preferences, needs and requirements. Existing steering systems do not allow for high level of flexibility in modifying the feedback and allowing drivers to make choices on what is ‘natural’ to them. Beyond ‘natural’, drivers can also be presented with the scope of directly adjusting the settings to their preference and liking. Since the feedback is tactile and continuous, allowing drivers to adjust such an interaction is likely to enhance their experience with the steering system and hence with the overall driving experience.

In this thesis, the design flexibility offered by SbW systems was partly explored to understand the needs and requirements for the driver while interacting with the steering system. Research focused on four main research questions presented in Chapter 1 of this thesis. The four questions will now be revisited and answered based on the discussions that emerged from the five studies presented in this thesis.

9.2. RESEARCH CONCLUSIONS

The aim of the research was to gain understanding of steering wheel feedback to generate design requirements, in the context of steering feel, for SbW systems. Another goal of the research was to generate requirements for an HMI based on research findings. Research objectives were defined by four research questions.

9.2.1 What is the impact of individual differences in preferences for steering effort?

From Chapter 2, which provides an overview of steering systems, it is clear that several interventions have been made by automotive manufacturers to assist drivers in overcoming the road wheel forces and mass of the system. The assistance (hydraulic or electric) resulted in reducing the steering effort for the drivers. With there being a single setting in most vehicles, drivers were required to adapt to the assistance designed into the system by car manufacturers. And with few studies showing existence of individual differences in preferences for steering feedback, there was a need to study if such preferences existed in particular for steering effort. The driving simulator study presented in Chapter 3 focused on studying how individual differences impact preferences for steering effort and also whether drivers preferred speed based power assistance. The study clearly showed that there are individual differences in preferences for steering effort, but also that factors such as gender did not have a significant effect. Results also clearly showed that drivers prefer speed based assistance as done in Variable Power Assist Systems (VPAS). Individual differences were observed within the framework of VPAS i.e., there are drivers who consistently prefer lower
feedback (increasing with speed), others who prefer moderate feedback (increasing with speed), and others who consistently prefer higher feedback (increasing with speed).

The findings are indications that preference for Force, an important element of steering feel, differs across individuals and driving speeds. Therefore, this leads to the conclusion that a single setting for steering effort does not meet the preferences for all drivers. The HMI design must take this into consideration and also retain speed-based power assistance. With gender having no significant effect on preference for steering effort, it appears that the HMI design does not need to take into account the gender of the driver. For instance there are interfaces on which settings are gender dependent, but for an HMI for SbW systems, this can be ignored. An interesting observation from the first study was the persistent referral by participants to Comfort and Control prior to making preferences. With participants stating that both factors influence their preferences, it was unclear as to specifically what they were referring to. It was also unclear as to whether they were making compromises between comfort and control to arrive at their final preference.

In addition to testing individual preferences, the first study also tested operational limits of the driving simulator. It was concluded that the simulator required upgrades to the steering wheel actuator to improve control over the steering wheel and flexibility in integrating steering models that could be manipulated in real-time.

9.2.2 What are the factors influencing individual preferences for steering effort and what impact does feedback torque have on these factors?

Comfort and control are key attributes associated with steering. Since the task of steering is continuous and safety-critical, it is necessary to ensure that there is sufficient comfort and control. The first study on preferences for steering effort found that Comfort and Control both influenced preferences for drivers. The impacts of feedback torque level on perceived comfort and control and on the driving performance were investigated through the second driving simulator study presented in Chapter 5. The primary aim of the study was to explore the impact of feedback torque level on perceived comfort and control i.e., about how perceived comfort and control vary with changes in feedback torque levels and whether there are distinct optima for the two. In addition, as discussed in Chapter 5, a clear definition of perceived comfort and control in the context of steering was unavailable. The study therefore also explored and presented the subjective attributes that define comfort and control.
Conclusions from the study reveal that there is an impact of feedback torque level on perceived comfort and control. The relationship between perceived comfort and control and feedback torque level was non-linear. It was found that perceived comfort and control were both low when drivers are exposed to unfamiliar feedback settings such as 0 Nm (no feedback torque). Perceived comfort and control both continued to increase when feedback torque was increased beyond 0.8 Nm and reached a peak in the 2.4 Nm – 4 Nm range. And beyond 4Nm when feedback torque continued to increase, it was found that perceived comfort and control decrease and drop sharply after 5.6 Nm.

The study was able to show that comfort and control were mutually dependent. Mutual dependence meant that there are no distinct optima for comfort and control. In exploring comfort and control, the study found that they are strongly related to experiences that drivers are familiar with while driving their own cars. This was also confirmed with high ratings for intermediate feedback torque levels (similar to feedback torque levels experienced in cars with power assistance) that were offered to participants in the study. Reliance on personal experiences meant that drivers’ perception of unfamiliar settings is likely to be less positive in regards to comfort and control. And this means that drivers would have to drive for a period of time with unfamiliar settings (except extreme settings such with feedback less than 0.8 Nm and greater than 5.6 Nm) to develop confidence. The study also found that comfort and control perceived in corners is different from straights. The finding leads us to conclude that steering torque (defined by the power assistance) must be a function of not just speed but also of steering angle as done in state-of-the-art steering systems.

9.2.3 How do changes in steering settings affect driving performance?

While subjective ratings and steering experiences are important, a SbW system design with different settings would be meaningless if the settings lead to deterioration in driving performance. And since steering is a safety critical task, it becomes increasingly important to study driving performance. Furthermore, the first two studies present conclusive evidence that there are individual differences in preferences for steering effort and that there is a wide range (0.8-5.6 Nm) offering moderate to high level of comfort and control. Due to the above mentioned reasons and to make concrete design recommendations for steering settings, it was important to study the driving performance with the different feedback torque levels. Analyses of driving data presented in Chapter 5 show that drivers are able to quickly adapt to the different levels of feedback torque after driving through a corner. Analyses showed that participants displayed similar levels of driving performance even with
an extremely high level of feedback torque which was rated poorly in terms of perceived comfort and control. In the absence of feedback torque (0 Nm), participants in the study displayed relatively poor performance compared to other levels offered. The overall ability of participants to quickly adapt to the different settings was surprising since participants were able to process steering feedback and adapt their motor control behavior quickly even with steering settings that they do not encounter in normal cars. In the simulator study, participants had to negotiate a series of curves with varying radii at different speeds and were still able to adapt their steering control behavior to deliver similar performance with the different levels of feedback torque.

Since the study described in Chapter 5 did not impose additional cognitive load, it was hypothesized that drivers were able to quickly adapt to even the extreme settings as they had all their cognitive resources available to process and deliver steering input. If cognitive resources are continuously loaded, drivers may not be in a position to pay attention to other factors impacting driving. And, in a realistic driving scenario, drivers can be engaged in a range of secondary tasks such as interaction with navigational systems, entertainment systems, social interaction with passengers, attending phone calls and texting that consume cognitive resources. While the secondary tasks are not always performed, when the difficulty of the driving task is lowered, drivers are provided with an opportunity to engage in such tasks which can enhance their driving experience. To test the above stated hypothesis and in view of the fact that drivers engage in secondary tasks while driving, the third driving simulator study presented in Chapter 6 was conducted. A running memory 4-back task was used as the secondary task. Results showed that even while continuously performing a secondary task while driving, drivers can quickly adapt to different levels of steering wheel feedback torque. With results rejecting the hypothesis, the conclusion is that drivers can easily adapt to even unfamiliar settings, except with zero feedback torque which again resulted in relatively poor performance. Hence when offered new settings with changes in feedback torque, drivers can easily adapt and deliver similar levels of performance.

Studies in the driving simulator focused on modifying the force component of steering feel and were able to clearly demonstrate that drivers were able to adapt easily to unfamiliar feedback torque settings. In the prototype SbW vehicle, more settings were tested and more components of steering feel. Settings varied Power Assistance Gain, Torsion Bar Stiffness, Boost Linearity, Steering Wheel Damping and Steering ratio in a steering model to vary the subjective experience of Force, Directness, Sensitivity, Return-to-Center Feel and Road Feel. The prototype was a more realistic test platform compared to the driving simulator. With
there being implications on safety with poor driving performance in an actual vehicle, it was expected that participants would take a more cautious approach by reducing speeds with unfamiliar settings and settings that receive poor ratings for subjective experience attributes. Poor lateral control performance was also expected when participants had to drive with unfamiliar settings. However, performance results presented in Chapter 7 and 8 along with subjective ratings clearly show that there is no impact of steering settings on driving performance. Even settings which received poor subjective ratings did not result in poor driving performance. The findings add external validity to results from the driving simulator which also showed that participants were able to adapt to unfamiliar settings. Overall, driving performance from the different studies clearly shows that participants can drive well with a wide variety of steering experiences under normal circumstances. The findings provide confidence in allowing engineers to conceptualize new steering settings as a setting that might be poorly rated by one driver may be rated well by another driver. A decision to implement them must be taken after extensive subjective evaluation as studies in this thesis have shown that performance is not related to preference and ratings for subjective experience attributes. Evaluations need to be conducted with a diverse group of participants to ensure the studies do not focus a particular set of drivers. The evaluations must take place in varying conditions of road surface, traffic and maneuvering (inclusion of double lane change test for example to test subjective experience during high speed maneuvering).

9.2.4 What is the mapping between parameters in the physical space and steering feel attributes in the subjective space?

The three experiments conducted in the driving simulator focused mainly on the ‘force’ component of steering feel. While feedback torque provides a sense of position and control over the vehicle, there is other information transmitted through the steering wheel such as road feel and characteristics of steering feel such as return-to-center and directness. Steering feel is a feeling comprised of several subjective experience attributes associated with characteristics of the steering wheel defined by steering parameters. Insight into the mapping between the subjective experience attributes and parameters of a steering model would therefore enable designers to create systems where drivers can modify a specific aspect of the steering feel to generate a desired experience. Two studies presented in Chapter 8 and Chapter 9 were conducted in a prototype SbW test-vehicle to explore the subjective experiences and map them to physical steering parameters. Five steering parameters (Power Assistance Gain, Boost Linearity, Torsion Bar Stiffness, Steering Wheel Damping and Steering Ratio) which can induce perceivable changes on the steering wheel
were chosen for both studies. The subjective experience space for these five parameters was explored and mapped. The mapping shown in Chapter 7 and Chapter 8 illustrates that there is a complex relationship that exists between subjective experiences and steering parameters. The mapping showed that the same subjective experience attribute can be altered by more than one parameter in the steering model. To highlight this point, it may be recalled from Chapter 7 that Power Assistance Gain and Torsion Bar Stiffness both affect perceived Force. Power Steering Assistance Gain also affects the perception of other subjective experience attributes such as Comfort, Safety, Control and Sensitivity, and Torsion Bar Stiffness also affects the perceived Road Feel. If the driver prefers to increase his Road Feel, the Torsion Bar Stiffness will be increased but this also increases perception of Force and Return-to-Center Feel. The increases in Force and Return-to-Center Feel might not be desired by the driver and there is no evidence to show that Road Feel is increased by increasing Force or Return-to-Center Feel. Hence, another parameter will have to be modified to ensure that Force and Return-to-Center Feel remain the same while perception of Road Feel is increased. Based on audio transcriptions and system response, it is evident that Road Feel is increased with increasing vibrations on the steering wheel. In a SbW system, vibrations can be introduced and controlled by haptic actuators while other characteristics of the steering wheel and feedback remain the same. Similarly, in existing steering models, an increase in Directness by decreasing the Steering Gear Ratio increases feedback torque and this undesired increase will have to be countered by changing other parameters.

The discussion from Chapters 7 and 8 shows that there are modulating variables which modulate the preferences for the subjective experience attributes and also higher order variables that must be associated with any new design changes in steering wheel feedback. The higher order variables are Comfort, Control and Safety. The required levels for these variables may change across individuals i.e., one driver may require a greater perceived level of Safety than another driver (Wilde, 1998; Fuller 2005). Hence, a personal baseline of these variables is considered by drivers in assessing the subjective experience attributes. The preferences for selecting a subjective experience attribute are then modulated by variables such as Driving Environment (built-up, rural), Driving Speed, Type of Co-passenger (infants, children, family), Driving Mood, Road Surface, Traffic Conditions and so on. The findings allow us to get an impression of the different variables which may influence driver preferences and more importantly show that differences in preference are not only across drivers but that preferences also vary for an individual based on different modulating
variables. With so many factors, it is not possible that a single setting can meet the need and requirements of all drivers.

9.3 LIMITATIONS

The research studies presented in this thesis offer understanding of steering feel and also driver preferences in regard to steering wheel feedback. The understanding gained is to be used as input towards the future development of SbW systems. But as discussed earlier in the introduction, a car is used by different types of individuals while designs must cater to the general population. In the research studies presented in this thesis, participants mostly comprised of young drivers who were either students or employees at Eindhoven University of Technology. While the population is representative of a normal young driver, there are also other sets of population such as older drivers and differently abled people who will use cars with SbW systems. Their needs and requirements also need to be studied as driving studies have shown that preferences can vary based on age and capabilities of the driver. Since by-wire systems make system functionality and operation flexible, if there is need for models catering for a particular target user group then that can be developed as well. Investigation involving different user groups, though required, was not carried out due to time constraints.

Research concluded that participants were capable of maintaining similar levels of driving performance even with unfamiliar steering settings. The addition of cognitive load also did not have an effect on performance with unfamiliar settings. Performance from the test-car and driving simulator were used to arrive at this conclusion. Performance studied in the test-car also validated findings from the simulator studies. The findings need to be taken into consideration for SbW development. However, longitudinal studies were not conducted to study if such levels of performance could be maintained over a period of time. Also performance in critical scenarios, for examples collision avoidance was not investigated due to time limitations. Testing in critical scenarios with a prototype vehicle would require professional test-drivers and a test-track suitable for such studies. Such studies may be valuable in expanding existing understanding of performance.

There were also time and resource constraints which did not make it possible to evaluate HMI designs that allowed personalizing steering feel. The prototype vehicle was made available for test purposes after two years into commencing research and also had to be shared with the Department of Mechanical Engineering to meet their research goals. While all efforts were made to maximize the advantage of the prototype vehicle, it suffered several
technical glitches which resulted in delays. The HMI development was only possible using onboard software which did not offer visual and interactive element that matched state-of-the-art interaction design. A demonstrator interface was developed, but creation of an interface for user tests would have required integration of external software applications offering state-of-the-art interactive features and visual aesthetics. In addition, studies would have had to be planned and executing for evaluating designs. Evaluation of the HMI might also have required longitudinal in-situ studies which could not have been conducted as the prototype car was not road legal. Existing legislations mandate the need for a mechanical linkage and couple between the steering wheel and road wheels, which the prototype car did not have.

9.4. STEER-BY-WIRE SYSTEM REQUIREMENTS

One of the aims of the research work was to generate system requirements for SbW by studying the users’ needs and expectations while interacting with the steering system. This section lists the needs, requirements and some associated findings based on the research work that was carried out in both the driving simulator and prototype test-vehicle. The findings if taken into account in the development of SbW systems, will provide drivers with new functionality in their vehicles and this may lead to significant improvement in user experience. The list is found below:

- Steering feel is a term that indicates a qualitative assessment of: a) the feedback characteristics of the steering wheel (force, road feel) b) behavior of the steering wheel (on-center feel, return-to-center feel, directness) c) response of the steering system and subjective experiences that arise due to a and b.

- ‘Natural’ steering feel and ‘Natural’ feedback are subjective terms associated with an experience that drivers are used to or familiar with.

- Steering feel assessments vary across individuals. Drivers can be presented with opportunities to personalize steering feel through an HMI according to their preference.

- Force, an important element of steering feel defined by the Power Assistance Gain parameter, must always be present and should not be increased beyond 5.6 Nm as it may cause physical discomfort.

- Customizable feedback torque settings can be provided. And, feedback torque must be a function of vehicle speed and steering wheel angle.
• The on-center feel must be defined with a stiff steering wheel when the road wheels are aligned to the dead-center point to ensure that drivers can be confident that the vehicle is going on center.

• Return-to-center characteristics must be present and drivers must be allowed to vary the rate of return as there are drivers who prefer the steering wheel to return to center point at different rates.

• Road Feel experience must be customizable as not all information on the road is required to be processed. While some drivers like to feel more connected to the road, there are also those who prefer such information to be suppressed unless it becomes safety critical – like for instance driving on ice.

• Road Feel experience can be controlled external to the steering model with embedded vibro-tactile actuators in the steering wheel.

• With the average driver having limited understanding of steering terminology, they must be able to alter subjective experiences rather than the physical parameters directly.

• Expert drivers on the other hand must be given the opportunity to also manipulate steering parameters directly.

9.5. HMI DESIGN RECOMMENDATIONS

It has been repeatedly stated in this thesis that drivers must be presented an opportunity to customize their steering feel on a Human Machine Interface (HMI). Discussions of results from the different studies categorically reinforce the need for such an HMI. Studies conducted in the prototype SbW vehicle provide a mapping between subjective experiences and steering parameters. However, the mapping being more complex than expected, more studies where multiple steering parameters are changed are required to come up with concrete proposals for HMI design. The design also needs to be evaluated prior to industrial development. During the course of this doctoral research, HMIs were developed for purely demonstrative purposes. Additionally, feedback was received on potential HMI designs for SbW systems from members of the User Centered Engineering Group at Industrial Design in a non-experimental setting. This section makes recommendations for HMI design based on findings from studies presented in this thesis.
The HMI for SbW systems must be integrated into the Vehicle Management System (VMS) of the car. The VMS system displays the system state of various systems in the vehicle and also allows turning on and off certain ADAS functions in the vehicle. Most cars today have a built-in touch screen panel to display and control the VMS, navigation, entertainment systems and so on. Keeping pace with the market, the HMI must be touch screen based. Some vehicles allow steering customization using physical buttons on the dashboard panel but with several options being proposed for the driver, physical buttons are not a good choice.

Even though the application of design principles such as those by Schneiderman (2003) might lead designers to offer presets such as Relaxed, Normal and Sporty on the HMI, that approach however might not be useful to drivers as the settings do not convey sufficient information on what has changed. Also, the subjective experience perceived in these settings can be completely contrary to the intention of the designers as there are individual differences. Such settings were also least preferred in the informal evaluations. Participants instead showed preference to manipulate subjective experiences such as Force, Road Feel, Return-to-Center Speed, Directness and so on. Here, it may not be meaningful to provide settings such as Comfort, Control and Safety since everyone would prefer these three to be high. For illustrative purposes, the HMI screen can be as shown in Figure 9.1.

![Figure 9.1 Example of customizable steering settings for drivers.](image)

In Figure 9.1, consider the values on the slider as default values for the car. The driver can change these values to the desired level by adjusting the sliders on the scale. If the driver
chooses to reset, then this is also possible by the driver by clicking on the RESET button which will reset to default values. When the required experience is changed, the system must make the appropriate changes in the steering model by varying parameter values. The parameter values will be based on subjective experience mapping to physical parameters. If the driver has expert knowledge of the system, they can choose EXPERT SETTINGS option for instance to manipulate steering parameters directly as shown in Figure 9.2.

![Figure 9.2. Example of expert settings.](image)

When the expert settings are varied, saturation limits must be enforced to ensure that the drivers do not adjust these parameters to system limits that may result in inoperable driving conditions. In the HMI, drivers must be only allowed to change the parameters to values where they can continue to deliver good driving performance for sustained periods of time. Here again the drivers have the option to return to the home screen if desired.

Directness must not be allowed to change during driving as these can result in sudden unintentional system calibration of the road wheels. The system must therefore verify the vehicle state prior to allowing drivers to change them.
It is possible that there are multiple people who drive a vehicle. If each person keeps changing the settings on the HMI every time they drive, it can cause inconvenience to users of the vehicle as they may have to re-adjust settings. If drivers are made to re-configure the steering system every time they drive, it is possible that they may not use the system. To avoid this problem, drivers must be allowed to save their preferences on the VMS. Additionally, the same driver may have created multiple configurations depending on the modulating variables discussed earlier. With an option to save settings, it makes things less complicated and more user-friendly.

The above mentioned example of an HMI was both by members of the User Centered Engineering (UCE) research group of TU/e and by visitors in a demonstration in an informal setting when it was compared against an HMI which offered settings such as Relaxed, Normal, and Sporty. Though the preset settings such as Relaxed, Normal, and Sporty were not preferred and as stated earlier can be perceived different by different types of users, commonly used devices as music players and televisions provide preset settings to allow users to experience different settings without having to manipulate individual dimensions. As mentioned before, use of presets in a driving context could enable drivers to have easy access to select a specific cluster of settings. Following presets, drivers may be given the option to make changes as shown in Figure 9.1 and 9.2. While the inclusion of an HMI for steering brings complexity to the system, it has the potential to improve in-car experience for the driver. On a more fundamental note, it may be argued that the HMI presenting customizable options may not be required as drivers tend to adapt to the settings provided. However, the trend of personalization to offer unique experiences for drivers has become a selling point for manufacturers and with users being much more willing to explore options provided they are user-friendly, presenting a well designed HMI in current scenarios is justifiable. Much more work is required in coming up with a final design for an HMI, which leads to directions for future work.

9.6. CONCLUDING REMARKS AND FUTURE DIRECTIONS

This thesis presented research work that was carried out with specific goals contributing to development of SbW systems to allow drivers the opportunity to modify steering feel according to preferences. While there are several focus areas that can be targeted for research, the research goals were designed taking into consideration the time and resource constraints. To achieve research goals, five experimental studies were conducted and presented in this thesis. The studies offered insight into how regular drivers perceive changes made to the steering wheel settings. Studies were conducted on a fixed-platform
driving simulator and also a prototype SbW vehicle. Based on the findings, this thesis concludes that there are individual differences in preferences for steering settings and that drivers must be allowed to make these preferences on an HMI. Furthermore, natural feedback is associated with the feedback that drivers have been used to. As different cars offer different steering feel, natural feedback can differ according to drivers. Also, cars today offer multiple preset settings that drivers can choose from to modify their driving experience. However, “natural” feedback is based on an individual driver’s desired steering feel defined by different subjective experience attributes that are mapped to physical steering parameters. These findings and developments in the automotive industry further highlight the need for an HMI that can be used to modify subjective experience attributes relevant to steering feel. The design for such an HMI requires a mapping between steering parameters and subjective experiences and studies that contribute to creating the mapping have been presented in this thesis. Such mapping may then be used to design different type of steering feel that the driver can select to enhance or vary the driver experience positively. Conclusions from the thesis have resulted in several recommendations for SbW systems and also for an HMI on which drivers can personalize steering feel.

This thesis has presented experimental studies which make contributions to the development of SbW systems and an HMI that allows personalization of steering feel. Next steps in HMI development would be to create an HMI and perform usefulness and usability studies on them. HMI design is likely to become a unique selling point for automotive manufacturers and designs are expected to differ across manufacturers. Research work focusing on longitudinal in-situ studies can provide more insight on how people use these systems and how their needs evolve when offered the scope to perform such changes to steering. Such studies can further aid the development of an HMI. Future work can also focus on studying the implications of SbW systems for Advanced Driver Assist Systems (ADAS) such as lane keeping assistance and lane departure warning. The advantage of SbW systems as stated is that the system can also make interventions to user input easily to enhance safety. For instance when the driver makes an unintentional lane departure, the system can choose not to react to the driver inputs and also warn them. The warning can be in the form of haptic feedback and the impact of this feedback on driving experience can also be studied. With ‘natural feedback’ varying across drivers, the haptic feedback design may require research on how to present them effectively for different types of steering feel. There are therefore several interesting human factors challenges where there is the need to understand how drivers react in different situations and design systems based on driver
behavior. The recommendations for future work further highlight the opportunities that SbW systems offer.
REFERENCES


APPENDICES
Appendix A.1

Upgraded Motor Specifications

ACM Brushless Series BRL 100-4

<table>
<thead>
<tr>
<th>Nominal Performance and Technical Features</th>
<th>BRL 100-4</th>
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<tbody>
<tr>
<td>Value</td>
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<tr>
<td>Number of Poles</td>
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<tr>
<td>Peak Current</td>
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Other Specifications

Degree of Protection : IP54-IP55-IP64-IP65 over 3000 only IP54 on the shaft
Accuracy of Rotation : DIN 42955 – class N or R
Shaft : Dimensions from project and key according to BS4235
Isolation Class : Class F-norm EN 60034-1
Degree of Balancing : Balancing of the rotor according BS6861-Q6.3 (or Q 2.5)
Temperature Sensor : Thermistor PTC with temperature interval 120° C
Vibration : According to IEC-34-12
Connectors : Cable/socket for power or connector 5 PIN
              Cable/socket for signal or connector 10/19 PIN

*Factory calibrated with the main drives on the market
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<td>Protrusion shaft (rear)</td>
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<tr>
<td>K</td>
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<tr>
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</tr>
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<tr>
<td>O</td>
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<td>R</td>
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**Terminal Box**

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<td>Height of the castlet</td>
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<td>Depth of the castlet</td>
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<tr>
<td>O</td>
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</tr>
<tr>
<td>R</td>
<td>Distance power socket</td>
</tr>
</tbody>
</table>
Appendix A.2

Upgraded Motor Drive Specifications

TDE MACNO – Mini OPENDRIVE EXP

AC input power:
1 phase / 3 phase 110 ÷ 230V ac
3 phase 230 ÷ 460V ac

Memory key connector
Keypad and display
Frequency output
Relays output
Frequency input
CAN bus line
RS-485 Modbus for PC programming and device interfacing
I/O analog / digital

DIGITAL & ANALOG I/O
- 8 digital inputs
- 2 digital outputs
- 3 analog inputs ± 10V
- 2 analog outputs ± 10V
- 1 stabilized supply ± 10V
- 1 relay output
- 1 integrated CANopen line
**FEEDBACK SENSORS**
- TTL Encoder
- TTL Encoder and Hall sensors
- Resolver
- Sin-Cos encoder (incremental and absolute)
- Ensat 2.1 and 2.2 encoder
- Bisa encoder

**Feedback options**
- UVW motor power connection
- R R for external braking resistor
- DC bus input (280V ÷ 750V)

**Shield cable management**

**24Vdc electronic supply and motor temperature sensor**
Appendix A.3

Simulator Vehicle Parameters

Audi A4 2008

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<td>Wheel mass</td>
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<td>kg</td>
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<td>Engine Volume, number of</td>
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<td>Maximum Torque</td>
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<td>--</td>
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<td>Brake distribution (front/rear)</td>
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<td>Inertia about world y-axis</td>
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<td>Vertical stiffness</td>
<td>12731 N/m</td>
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<td>Vertical damping</td>
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<td>1 kg.m²</td>
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<tr>
<td>Inertia about world y-axis</td>
<td>1 kg.m²</td>
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<td>Inertia about world z-axis</td>
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<tr>
<td>Vertical stiffness</td>
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<td>Vertical damping</td>
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Appendix B.1

Chapter 5 Questionnaire to study Perceived Comfort and Control

**Steering Wheel Force Comparison**

**Force Levels ____ Vs _____**

Compare the two force levels in terms of the attributes provided below. Make a choice of *More* or *Less* based on your experience with the two force levels and state how much more or less on a scale of 1 to 5.

1 – Very Small Difference

2 – Small Difference

3 – Moderate Difference

4 – Big Difference

5 – Very Big Difference

For example if your choice is

*More Heavy* and you select 3, then it indicates that you find the second level to be more heavy compared to the first and that you find the difference in terms of heaviness to be *moderate.*
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<th>Less Heavy</th>
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<td><em>By how much?</em></td>
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<td>1 Very Small</td>
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<tr>
<td>2 Small Difference</td>
<td></td>
</tr>
<tr>
<td>3 Moderate Difference</td>
<td></td>
</tr>
<tr>
<td>4 Big Difference</td>
<td></td>
</tr>
<tr>
<td>5 Very Big Difference</td>
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<td><em>By how much?</em></td>
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<tr>
<td>1 Very Small</td>
<td></td>
</tr>
<tr>
<td>2 Small Difference</td>
<td></td>
</tr>
<tr>
<td>3 Moderate Difference</td>
<td></td>
</tr>
<tr>
<td>4 Big Difference</td>
<td></td>
</tr>
<tr>
<td>5 Very Big Difference</td>
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<table>
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<tr>
<td>2 Small Difference</td>
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<td>4 Big Difference</td>
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Requires MORE Attention to Handle Vehicle

By how much?

1 Very Small
2 Small Difference
3 Moderate Difference
4 Big Difference
5 Very Big Difference

Requires LESS Attention to Handle Vehicle

Offers MORE Control While Turning

By how much?

1 Very Small
2 Small Difference
3 Moderate Difference
4 Big Difference
5 Very Big Difference

Offers LESS Control While Turning

Offers MORE Control while driving on Straights

By how much?

1 Very Small
2 Small Difference
3 Moderate Difference
4 Big Difference
5 Very Big Difference

Offers LESS Control while driving on Straights

Offers MORE Comfort While Turning

By how much?

1 Very Small
2 Small Difference
3 Moderate Difference
4 Big Difference
5 Very Big Difference

Offers LESS Comfort While Turning
Offers MORE Comfort while driving on Straights Offers LESS Comfort while driving on Straights

By how much?

1 Very Small
2 Small Difference
3 Moderate Difference
4 Big Difference
5 Very Big Difference

Requires MORE Mental Effort Requires LESS Mental Effort

By how much?

1 Very Small
2 Small Difference
3 Moderate Difference
4 Big Difference
5 Very Big Difference
Appendix B.2

Chapter 7 Questionnaire: Subjective Experience Attribute Ratings in Comparison to Baseline

1. Force

Extremely | No | Extremely
Lower | Difference | Higher

2. Road Feel

Extremely | No | Extremely
Lower | Difference | Higher

3. Sensitivity

Extremely | No | Extremely
Lower | Difference | Higher
4. **Return-to-center Feel**

```
-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
```

Lower Difference Higher

5. **Sluggishness**

```
-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
```

Lower Difference Higher

6. **Directness**

```
-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
```

Lower Difference Higher

7. **Control**

```
-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5
```

Lower Difference Higher
8. **Comfort**

-5  -4  -3  -2  -1  0  +1  +2  +3  +4  +5

Extremely  No  Extremely

Lower  Difference  Higher

9. **Overall Steering Feel**

-5  -4  -3  -2  -1  0  +1  +2  +3  +4  +5

Extremely  No  Extremely

Lower  Difference  Higher
Appendix B.3

Chapter 8 Questionnaire: Subjective Experience Attribute Ratings without Baseline Comparison

Rate the following experiences

(circle the number as appropriate)

1. Force
   1  2  3  4  5  6  7
   Low   High

2. Road Feel
   1  2  3  4  5  6  7
   Low   High

3. Sensitivity
   1  2  3  4  5  6  7
   Low   High

4. Return-to-center Feel
   1  2  3  4  5  6  7
   Slow  Fast

5. Directness
   1  2  3  4  5  6  7
   Low   High

6. Control
   1  2  3  4  5  6  7
   Low   High

7. Comfort
   1  2  3  4  5  6  7
   Low   High

8. Safety
   1  2  3  4  5  6  7
   Low   High

9. Overall Steering Feel
   1  2  3  4  5  6  7
   Low   High
ACKNOWLEDGMENTS

First and foremost, I would like to thank Dr. Jacques Terken for having me as his student for this wonderful opportunity at Eindhoven University of Technology (TU/e). I appreciate all his contributions of time, ideas, creating networking opportunities, actively co-authoring publications and also leading by example through his professional conduct and attitude. We have shared many interesting conversations on the subject of steering, experimental design, statistics and driving in general. You have always had your door open for me to discuss research and personal issues and have gone well beyond what I had expected in a supervisor. With a deep sense of gratitude, I say that I am very lucky to have been supervised by you.

I would like to thank Prof. Dr. Ir. Berry Eggen, my promoter and beloved head of our User Centered Engineering (UCE) research group in the Department of Industrial Design. I am very thankful to your research guidance and for providing strong administrative and financial support to my research activities. You were very supportive throughout the years and your positive attitude has been infectious. I am particularly thankful for you in taking pains to ensure I was able to obtain the Dutch Driving License to carry out field tests with the prototype vehicle. Thank you for being there as a pillar of support and ensuring I felt at home working in the UCE group.

I thank Ir. Jeroen Hogema for acting as subject matter expert and being an external advisor on my research activities. I am deeply thankful for you often taking time off your busy schedule and attending meetings with myself and Jacques to advise on research plans. I have admired your professional attitude and to-the-point approach. Interactions with you have always been a learning experience. Your contributions as co-author in publications, in my view, have never failed to raise standards of the content. I thank you for being part of my PhD committee and providing invaluable feedback in improving this thesis.

I would like to thank Tom van der Sande from the Department of Mechanical Engineering for his work on the SbW test car and for his time in experiment planning, conducting user tests, participant recruitment and also analysis of data from the test-car. Tom, you have been a thorough professional and a great joy to work with. I am thankful that you were there and always willing to assist with whatever that was required. I have been in awe of the pace with which you work and your commitment and work ethics have been very inspiring as well. And thanks to your wild side, I have had some very memorable moments riding the test-car with you behind the steering wheel. I also thank Erwin Meinders from Mechanical Engineering for his assistance in helping conduct experiments with the test-car.

For his kind guidance and support in planning and conducting experiments with the test-car and also being on my committee, I would also like to thank Prof. Dr. Henk Nijmeijer.
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I would also like to thank Prof. Dr. Ir. Max Mulder and Prof. Dr. Ir. Manfred Tscheligi for being on my committee and providing feedback that helped finalize the thesis.

The driving simulator at Industrial Design served as the primary test-bed for my research activities and there have been many people who have helped me work with it and develop it further for my research. Alex Uyttendaele and Qonita Shahab of the UCE group were the first people to get me familiarized with the driving simulator. I thank Alex for investing a significant amount of time in helping me get familiarized with the driving simulator and conduct the first study. He also single-handedly reorganized the simulator room and created a control station which greatly helped conduct user tests. Thank you Alex for being there, helping me and being a driving force in spending time with the simulator.

I also acknowledge and thank Qonita’s contributions in helping me get familiarized with the simulator. Much of our time at the TU/e and central point of discussion revolved around the driving simulator. You have been very kind and supportive of my upgrades and constant changes to the “start-up” mechanism of the simulator. Over time, we began to discuss our research and shared cultural stories from our countries. I will cherish our conversations and also our conversations that pulled me tough moments on the journey we shared while writing our thesis.

I would like to thank Javier Quevedo who also helped me alongside Alex during the initial days I spent with the simulator. Javier, next to whom I sat in the UCE PhD space, has also been a good friend and continuous source of entertainment in the office with his sense of humor. Even the toughest moments can breeze through in his presence. I find it hard to imagine the good moments at TU/e without Javier.

I would like to thank Juan-Carlos Sanchez for his tireless efforts in incorporating a real-time steering control model in the driving simulator. His success opened new avenues for research studies with the simulator.
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Swethan Anand was born on 28-07-1986 in Chennai, India. He finished his undergraduate study in Mechanical Engineering in 2007 at Anna University (St. Joseph’s College of Engineering) in Chennai, India. He graduated with distinction and was awarded the Best Outgoing Student Award in Mechanical Engineering from St. Joseph’s College of Engineering. He then pursued his master study in Industrial and System Engineering specializing in Human Factors Engineering and Ergonomics at Virginia Polytechnic Institute and State University (Virginia Tech) in Blacksburg, USA. On completion of his master study in 2009, from January 2010 he started his PhD research at the Eindhoven University of Technology working in the User Centered Engineering research group within the Department of Industrial Design. This dissertation is a result of his PhD research in the area of by-wire steering systems.