Individual Differences in Preferred Steering Effort for Steer-by-Wire Systems

Swethan Anand
Eindhoven University of Technology
P.O Box 513, 5600 MB Eindhoven
The Netherlands
s.anand@tue.nl

Jacques Terken
Eindhoven University of Technology
P.O Box 513, 5600 MB Eindhoven
The Netherlands
j.m.b.terken@tue.nl

Jeroen Hogema
TNO Mobility
P.O Box 23,3769ZG Soesterberg
The Netherlands
jeroen.hogema@tno.nl

ABSTRACT

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 that include factors such as age, gender and driving style. These differences have mostly been established by subjective evaluations and comparative studies, where participants were unable to modify steering effort actively while driving a vehicle. This paper describes an experiment conducted on a driving simulator designed with a user interface that allows participants to actively modify steering effort settings on the steering wheel, to investigate the effect of gender on preferences for desired steering effort and personalization of future steering systems. Participants in the study performed multiple driving tasks on the simulator while interacting with the user interface to vary steering effort and subsequently reported their preferred level. Results from the study indicate individual differences exist with respect to preferred steering effort, although gender does not significantly impact the preference for steering effort. On the basis of the findings we propose a recommendation for the design and development of by-wire steering systems.

Categories and Subject Descriptors

H.5.2 [**User Interfaces**]: Input Devices and Strategies, Interaction Styles, User-centered Design

General Terms

Design, Human Factors

Keywords

Steer-by-wire, Human Machine Interface, Steering Systems, Steering Feel, Steering Effort

AutomotiveUI'11, November 29-December 2, 2011, Salzburg, Austria

1.INTRODUCTION

Steering systems have evolved into complex systems for management of vehicle handling [1] [2]. Technological advances have resulted in innovations that contribute towards improved vehicle handling performance and driver comfort [2]. One of the factors associated with vehicle handling is steering effort. With power steering becoming a standard feature, steering effort has been considerably reduced when compared with earlier steering systems [3]. While the reduction in steering effort is usually fixed by the manufacturer and cannot be customized by the driver, studies have shown that the preferred level of steering effort may vary across individuals based on factors such as age, gender, driving style [4] and driving scenario [4][5][6]. Steer-by-wire systems, which have become possible through advances in electronics, create novel opportunities for suiting the needs of different drivers [7] [8]. In this paper we present a study on the effect of gender on preferred steering effort for Steer-by-wire systems. The paper also explores variations in preferences for steering effort across different driving scenarios.

1.1 Steer-by-wire systems

Steering is an operation that requires drivers to constantly interact with the steering wheel to control lateral movement and maintain vehicle stability. Movement of the steering wheel is the input command signal from the driver to actuate the steering gear mechanism. In existing steering systems, signal transmission from the steering wheel takes places mechanically via the steering column, a cylindrical metal shaft connected to the steering wheel. When the steering gear mechanism is actuated, force proportional to that of the input signal is applied to the road wheels. Force application moves the road wheels from center position to produce desired lateral effect. The design of road wheel fixture and alignment however induces return-to-center motion of the road wheels while turning [9]. This in turn generates forces on the steering wheel that act against the direction of rotation of the steering wheel by the driver. The reactive force transmitted via the steering column onto the steering wheel as reactive torque provides drivers with information relating to the movement of the road wheels. The information is used to control steering [3] [10]. The reactive torque has to be overcome to enable further movement of the wheels with some amount of effort by drivers [9]. The effort exerted by the driver to overcome the resistive force in order to move the steering wheel is referred to as steering effort.

In advanced steering systems, steering effort is significantly reduced with the help of power assistance from the system. The amount of assistance offered depends on built-in steering settings [3]. These settings vary across vehicles and can typically not be modified by the driver (although there are some vehicles that have a 'city' setting for the steering system to reduce steering effort). This creates a scenario where drivers have to adapt to the settings offered by the system - a scenario in contradiction to basic principles of user-centered design. Anecdotic evidence that not all drivers are satisfied with this situation comes from the fact that there are people who prefer to drive old-timers, i.e., vehicles dating from before the era of power steering, because in their opinion there is a much more direct feedback link between the steering wheel and the road wheels and it feels much more like real driving, while power steering is felt as "spongy".

In Steer-by-wire systems the mechanical connections between the steering wheel and the road wheels are replaced by electronic components. Sensors detect the movements of the steering wheel, which are translated into commands for actuators that control the turning of the road wheels. Since there is no mechanical connection between the road tyres and the steering wheel, steer-by-wire systems have no reactive torque [8]. In order to create a "natural steering feel", sensors detecting forces on the road wheels are translated into commands for actuators that simulate the reactive torque on the steering wheel according to a certain transfer function. Much work has gone into creating such a natural steering feel [11] [12] [13], although it is not fully clear what "natural" means, so that it may be more appropriate to talk about satisfactory steering feel. Steer-by-wire configurations make it possible to adjust the transfer function to the needs of the situation, and, if desirable, to enable the driver to adjust the steering effort to his/her personal preferences [1] [8] [14] [15]. A challenge for research is then to determine what 'satisfactory' means, and how it relates to the situation and individual characteristics and preferences as well as performance of drivers.

1.2 Related Studies

Studies conducted in the past have shown that preferences for steering effort vary across individuals on a number of factors that include age, gender, driving experience and driving style.

A study conducted by Barthenheier [4] illustrates some of these individual differences for preferences of steering parameters, 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 give rise to steering effort and subsequently steering feel in these driving situations, varied significantly across individuals based on age, gender and driving style. The driving situations require 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 [5] also show 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 Barthenheir however has also been supported by an earlier study [6], which indicated gender may affect preferences for steering effort. The automotive industry has also taken cognizance of 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 can create conditions of oversteer and understeer, which can lead to potentially life threatening situations and result in roll-over of the vehicle during oversteer [16].

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 [1] [13] [17] [18]. 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 well defined.

An experiment was therefore conducted to investigate variations in preferences. 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 reactive 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 reactive torque. The experiment conducted also aimed to understand how steering settings could be programmed to create a personalized system if preferences for steering effort varied significantly.

2. METHOD

2.1 Experimental Design

The experiment followed a mixed methods 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.

2.2 Materials

A pre-task questionnaire was administered to gather personal 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.

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 Figure1.

Figure1. Driving environment view on the simulator.

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 mechanism therefore underwent the following changes to produce variable steering torque, which then generated varying steering effort that could be controlled by participants using an interface on the steering wheel. The simulator made use of a brushed DC motor to generate reactive torque. The motor was controlled by a Arduino Duemilanove microcontroller and motor driver. Control over the (Pulse Width Modulation) PWM resulted in control over the reactive torque produced. Having established external control over the feedback motor, the user interface had to be designed to allow participants to manipulate steering effort while driving.

2.4 User Interface to Control Steering Effort

A push button interface was built onto the steering wheel to enable seamless variation of steering effort manually by drivers while driving the vehicle. Two push buttons as shown in Figure2 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 buttons were 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 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 LCD display was used. The display was positioned similar to a GPS device and interfaced with the Arduino using Sketchify, a prototyping design program developed by Eindhoven University of Technology, to display the steering effort level. Levels were displayed to participants as text labels such as Level 1, Level 2 … Level 6.

Figure2. Push-button interface built on the steering wheel.

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 Table1. The torque was applied as a constant torque when the steering wheel was moved away from the center. Subjects were thus able experience maximum torque of a particular level instantly when moving away from the center to turn or overtake.

Table 1. Measures of reactive torque across six levels of steering effort.

Steering Effort Level	Measured Torque (Nm)
Level 1	0.84
Level 2	2.24
Level 3	2.95
Level 4	3.85
Level 5	5.78
Level 6	6.90

2.6 Experimental Task

The experimental tasks required participants to drive through four scenarios and execute the required steering maneuvers to maintain lane position and control of the vehicle. The simulator program was designed to simulate various driving scenarios where drivers had to execute different kinds of steering maneuvers to maintain vehicular control. For the experimental study, four driving scenarios were selected: 1) Parking_Reverse 2) City 3) Countryside 4) Highway. The selected scenarios required participants to execute different kinds of steering maneuvers to maintain control of the vehicle. Subjects drove a simulated Audi A3 vehicle during the experiment. 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 each of the three conditions in these two scenarios, participants were asked to report their preferences for these conditions as well. The Highway driving environment, however, required participants to navigate through straight lanes and few gradual curves, participants only reported a single preference level. Images of the circuits for the scenarios are shown in Figure3.

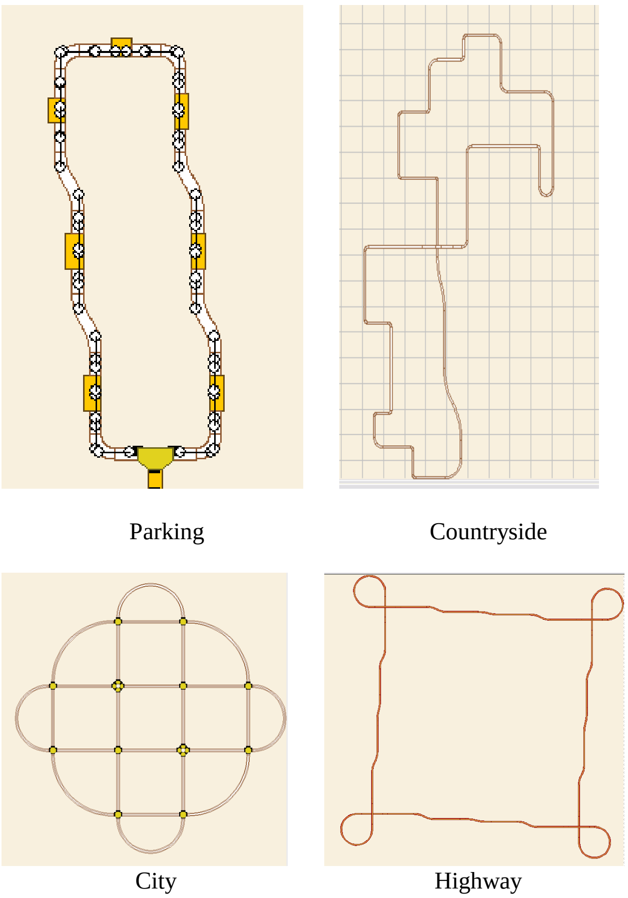

Figure3. Track overview for the four driving scenarios.

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 Figure4. The Parking_Reverse driving environment included several parking spots where participants had to park the vehicle by moving forward and reversing as is done normally. Parallel parking and perpendicular maneuvers were executed by participants. Participants reported a single preference level for the Parking_Reverse scenario.

Figure4. Screenshot of traffic in the Highway Scenario

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 increased 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 while driving and state their subjective opinion of each level in general terms. This was done to elicit natural subject response to a force level and identify specific terms using which they differentiated these levels. Participants always began driving at Level1 (the default start setting) 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 make 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. Participants therefore received the instructions 4 times. The order of scenarios was chosen to reduce simulator sickness and enable participants to complete the experiments. 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. Therefore Parking_Reverse scenario was provided at the end preceded by Highway, which was suggested to be most easy and comfortable by pilots. The order of the first two scenarios, City and Countryside, was selected at random. On completion of the experimental task in the four scenarios, participants were administered the post-task questionnaire to complete their participation.

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 recruited for the study 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 10 months (26 years 3 months for males, 25 years 6 months for females), ranging from 19 to 45 years and a driving experience of 5.46 years(6.04 Males, 4.88 Females), ranging from 2 to 12 years.

3. RESULTS

Means were computed across subjects separately for male and female participants. For the City and Countryside scenarios, a distinction was made between Sharp Curves, Gradual Curves and Straights, 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 Figure5.

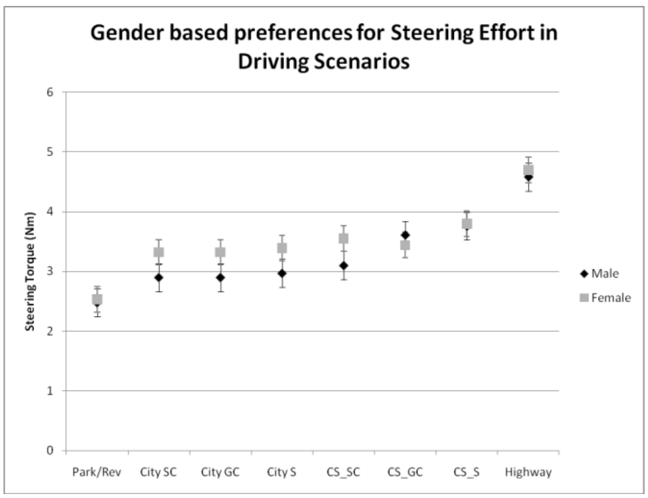

Figure5. Means ±1 standard error for preferred steering effort setting for males and females in different driving conditions. The x-axis represents the Parking_Reverse (Park/Rev), City Sharp Curves (City SC), City Gradual Curves (City GC), City Straights, Countryside Sharp Curves (CS_SC), Countryside Gradual Curves (CS_GC), Countryside Straights (CS_S) and Highway conditions.

A Kolmogorov-Smirnov test was conducted on the reported preferences for steering effort in the different scenarios provided. All distributions were non-normal. Consequently, non-paramteric analyses were used for all subsequent analyses.

A Friedman's ANOVA was first carried out 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 the City (χ^2 (2) = 0.4, $p > .05$) scenario. While interestingly for the Countryside scenario results revealed that the reported preferences for the three conditions varied significantly (χ^2 (2) = 8.313, $p < .05$), a post-hoc Wilcoxon signed ranked test was unable to significantly point towards how the preference varied across the three conditions. Therefore the three conditions for both the City and Countryside 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 analysis.

The scores for preferred steering effort from the four different scenarios were then analysed to look for significant differences in preferences for steering effort across gender. This was done by running a Kruskal-Wallis test across the four scenarios with gender as the grouping variable. The effect of gender was not significant in any of the four scenarios as can be seen in Table2.

Table 2. Effect of gender in the four driving scenarios.

Scenario	*H* values	*p* values
Parking_Reverse	0.255	0.613
City	0.017	0.897
Countryside	0.003	0.958
Highway	0.239	0.625

A Friedman's ANOVA however revealed that the main effect of scenario on preferred steering effort was significant (χ^2 (3) = 38.058, $p < .001$).

Looking at the graph in Figure 5, it can be seen that variations in preferences for steering effort were more diffuse at medium speeds compared to high and low speeds, where preferences appeared to converge. 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. The difference may arise from the criteria against which preferences were made. In studies conducted by Barthenheier[4], 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.

Although the effect of Gender was not significant, closer inspection of the data for individual participants as shown in Table3 indicated that there were differences in preferred levels of steering effort between individual participants.

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.

This progression is statistically significant, as shown by the outcomes of pair-wise comparisons by means of Wilcoxon's matched-pairs signed-ranks test: Parking_Reverse vs. City: Z = 2.87, p =.004; Parking_Reverse vs Countryside: Z = 3.60, p = .000; City vs Highway: Z = 3.24, p = .001; Countryside vs Highway: Z = 3.6, p =.000. Furthermore, in this pairwise comparison the difference between City and Countryside was also significant: Z = 2.15, p = .03, contradicting projections from Figure5 which appeared to suggest that preferences may not vary significantly.

Table3. Mean preferred steering effort (in Nm) for individual participants in Parking_Reverse, City driving, Countryside driving and Highway driving.

Gender	Parking_Reverse	City	Countryside	Highway
M	0.84	0.84	0.84	2.95
M	0.84	2.24	5.58	6.90
F	0.84	2.78	3.25	5.78
M	0.84	3.85	3.85	0.84
M	2.24	2.24	2.24	3.85
F	2.24	2.71	3.85	2.95
F	2.24	2.95	2.95	2.24
M	2.24	2.95	2.95	2.95
F	2.24	2.95	3.66	3.85
F	2.24	2.95	2.95	5.78
F	2.24	2.95	2.95	5.78
M	2.24	2.95	3.85	6.90
M	2.24	3.25	3.55	3.85
F	2.24	3.85	3.55	5.78
M	2.24	3.85	3.85	6.90
M	2.95	2.24	2.24	2.95
F	2.95	2.95	3.85	3.85
M	2.95	2.95	3.55	3.85
F	2.95	2.95	3.55	5.78
F	2.95	2.95	2.71	5.78
M	2.95	3.55	4.19	6.90
F	2.95	3.85	5.78	3.85
F	2.95	3.85	3.85	5.78
M	3.85	3.85	2.95	3.85
F	3.85	5.78	3.89	3.85
M	5.78	3.25	5.78	6.90

A box-plot (as shown in Figure6) of the preferred steering effort constructed for each scenario shows the overall trend of preferences across invidual subjects. The plot indicates that steering effort should increase with speed, mimicking the well established connection between reactive torque and speed as in conventional system while also showing that there are individuals who do not prefer such settings as can be evidenced by the outliers. 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.

As evident from Table3 and Figure6, 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 Reverse Parking, for the other scenarios there is a much larger variation, so that a fixed setting, for instance between 2 and 3 Nm, appears to be less in agreement with the preferred levels as set by the participants.

From this observation we conclude 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

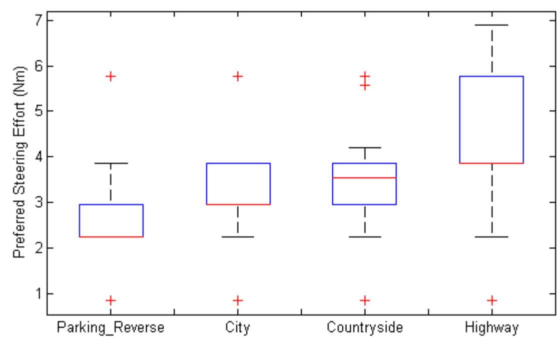

Figure6. Box-plots for preferred steering effort across the four driving scenarios.

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 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.

4. DISCUSSION AND CONCLUSION

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 based on the driving scenario, the study failed to confirm that gender significantly impacted preferences as reported in earlier studies.

Several reasons may have contributed to the fact that, unlike Barthenheier's study, the current study did not find an effect of gender on preferred steering effort. Firstly, 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 had approximately 200 participants[4].

Secondly, participants were provided a user interface to actively change and experience varying levels of steering effort while reporting their preferences, while in related studies the experimenter maintained control in modifying steering effort. Finally, participants were allowed to select preferred steering effort values without a selection criterion, unlike Barthenheier's study. So, there is no conclusive evidence that females in general prefer lower levels of steering effort. In addition, if significant differences would have been found with a larger sample, extrapolating from the current sample size they might have been small anyway.

Participants also offered mixed reactions to the push button user-interface provided on the steering wheel (the primary HMI) in the post-task questionnaire. 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. The study was limited in terms of the manner in which feedback was produced on the steering wheel. While the force feedback range and vehicle response to steering input followed simulations using real vehicle model, speed perception and ability to sense tyre-road surface interactions were limited.

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 have been found to play a pivotal role in the selection of preferred steering effort.

In future studies 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. Given that so far we cannot tell which driver characteristics influence reasons for preferring lower or higher levels of steering effort and that individuals differences will always exist; studies that instead focus on driving performance, driver behavior in relation to variation in steering effort and other steering feel parameters are to be carried out 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. Future studies will also try to understand in greater detail the information transfer between the steering system and driver via the steering wheel to design steer-by-wire systems that offer optimal information to the driver at preferred steering effort.

5. ACKNOWLEDGEMENTS

This research was made possible through a grant from The Dutch Ministry of Economic Affairs to the HTAS project VERIFIED.

6. REFERENCES

[1] Verschuren, R., and Duringhof, H.-M. "Design of a Steer-by-Wire Prototype." *SAE Technical Paper No 2006-01-1497*

[2] Walker, G. H., Stanton, N. A., & Young, M. S. (2001). Where is computing driving cars? *International Journal of HumanComputer Interaction, 13, 203–229.*

[3] Gualino, D.; Adounkpe, I.-J , "Force-Feedback System Design for the Steer-By-Wire: Optimisation and Performance Evaluation," *Intelligent Transportation Systems Conference, 2006. ITSC '06. IEEE* , vol., no., pp.181-187, 17-20 Sept. 2006

[4] Barthenheier, T. and Winner, H. *Das persönliche Lenkgefühl*, Vortrag auf der Fahrwerk.tech 2003, Fachtagung des TÜV-Süddeutschland, München, 2003.

[5] Bertollini GP, Hogan RM 1999 Applying Driving Simulation to Quantify Steering Effort Preference as a Function of Vehicle Speed. *Society of Automobile Engineers, 1999-01-0394, 1999*

[6] Green P, Gillespie T, Reifeis S, Wei-Hass L, Ottens O, Subjective Evaluation of Steering Effort Levels. *University of Michigan Transportation Research Intstitute UMYRI-84-39*

[7] Canudas-de-Wit, C., and Billot. P., "Human-friendly control design for drive-by-wire steering vehicles," *Proc. IFAC Adv. Automotive Control Workshop, Karlsruhe, Germany, Mar. 2001, pp. 28–30*

[8] Amberkar S., F. Bolourchi, J. Dmerly, S. Millsap, A Control System Methodology for Steer-by-Wire Systems, *2004 SAE World Congress, Steering and Suspension Technology Symposium*, Detroit, 2004

[9] Kim, J. and Song, J., Control Logic for an Electric Power Steering System Using Assist Motor. *Mechatronics, 2002. 12: p. 447-459.*

[10] A.C. Newberry, M. J. Griffin and M. Dowson, Driver perception of steering feel, *Proceedings of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering, 221, 405-415, 2007*

[11]Asai, S., Kuroyanagi, H., Takeuchi,S., "Development of a SBW system with force feedback using a disturbance observer", *2004 SAE World Congress, Steering and Suspension Technology Symposium*, Detroit, 2004

[12] M. Segawa, "A study of reactive torque control for SBW system", Proceedings of 7^{th} Annual Symposium on Advanced Vehicle Control, 2002.

[13] D. Odenthal, T. Bunthe, H. D. Heitzer, and C. Heiker, "How to make SBW feel like power steering", *Proceedings of the* 15^{th} *IFAC World Congress on Automatic Control, Barcelona, 2002.*

[14] Onoda. Y., et al, "Design Concept and Advantages of Steer-by-Wire System", *SAE Steering and Suspension Technology Symposium,SP 2189, 2008.*

[15] P.Yih, J.Ryu, and JC Gerdes. Modification of vehicle handling characteristics via stee r-by-wire. *Proceedings of the 2003 American Control Conference, Denver, CO, pages 2578–2583, 2003*

[16] Metz. L.D., "What Constitutes Good Handling?", *Proceeding of the 2004 SAE Motorsports Engineering Conference and Exhibition, Dearborn, Michigan., 2004.*

[17] Tajima, J., et al "Effects of Steering System Characteristics on Control Performance from the Viewpoint of Steer-by-Wire System Design",*1999 SAE Vehicle Dynamics and Simulation, 1999-01-0821, 1999.*

[18] Oh, S., Yun, S., Chae, H., Jang, S. et al., "The Development of an Advanced Control Method for the Steer-by-Wire System to Improve the Vehicle Maneuverability and Stability, *Proceedings from 2003 SAE World Congress, Detroit, Michigan, March 3-6, 2003.*