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Acceptance of Haptic Shared Control Design Choices for Car Steering

Kelsey N. Huijsing, Daan M. Pool, Marinus M. van Paassen and Max Mulder

Abstract—Haptic shared control systems that support drivers by means of added torques on the steering wheel are often tuned heuristically. To allow for more systematic design, this paper focuses on the Four Design Choices Architecture (FDCA) and systematically analyzes its tuning with an offline simulation model for the driver's control behavior and neuromuscular system. These analyses indicated that within the FDCA architecture the Level of Haptic Support (LoHS), which is a feedforward channel supporting negotiation of upcoming curves, is a main contributor to joint system performance. In a driving simulator experiment, the adaptation to and acceptance of different LoHS levels was investigated. Driver acceptance was found to increase with increasing LoHS values up to 1. Objective metrics, including torque conflict (70% reduction), steering effort (81% reduction), steering wheel reversal rate, and lateral deviation all improved, indicating that with the FDCA a high LoHS is both acceptable and, in fact, preferred.

I. INTRODUCTION

Haptic Shared Control (HSC) is a control architecture that enables a human to control a system (e.g., steer a car) together with an automated agent [1], [2]. When applied to a car steering task the human driver remains actively involved in the control loop and can be aware of the automated agent's actions on the steering wheel [1], [3]–[5]. However, HSC system design is sensitive to tuning, and an improper design may result in conflict torques between automation and human users [6]. This paper investigates the Four Design Choices Architecture (FDCA), which proposes key design considerations for HSC systems [3], see Fig. 1.

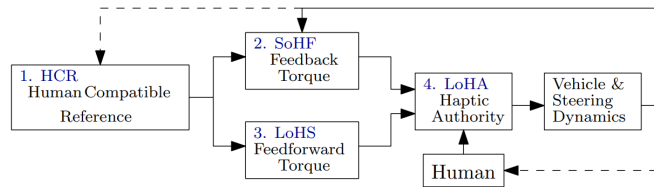


Fig. 1: FDCA structure and its design parameters.

The FDCA identifies four elements in an HSC system. The first is the *Human-Compatible Reference* (HCR), which describes a reference control behavior for the automation. The haptic guidance uses a feedforward component, the properties of which determine the *Level of Haptic Support* (LoHS) and a feedback component, characterized by the *Strength of Haptic Feedback* (SoHF). Finally, the *Level of Haptic Authority* (LoHA) sets the overall control authority of the haptic automation by adjusting the stiffness of the steering wheel. Together, these four design choices enable

shaping the feel of the HSC, its interaction with the human driver, and thereby the HSC's acceptance. The FDCA provides an alternative to iterative and heuristic tuning of haptic feedback [3], [7], where especially the explicit separation of feedforward guidance (LoHS) and feedback corrections (SoHF), see Fig. 1, has shown great potential. Previous research has indicated that the HCR can be adjusted to match individual drivers, in order to reduce conflict [8]. In this paper, we investigate the relationship between the LoHS and driver acceptance.

This paper starts by discussing the preliminary simulations in Section II, which were performed to gain an initial understanding of the cooperation and conflict between human and automation. Subsequently, the driving simulator experiment will be explained in detail in Section III. Hereafter, the data analysis procedure is treated in detail and the results are summarized in Section IV. Finally, the results are discussed and conclusions are drawn in Section V.

II. SIMULATIONS

Preliminary simulations were performed to assess how the driver and the haptic support may interact, depending on key parameter settings. Firstly, the parameters of a human driver model are varied for a single curve with the intent of establishing their sensitivity on the resulting lateral trajectory and the combined steering output. The results are used to create a realistic HCR for the FDCA. In the second set of simulations, the output HCR from this driver model is used as a reference for the haptic FDCA controller in the complete HSC simulation. This simulation is used to study the effects of changing the FDCA design parameters [9], here focusing primarily on the LoHS (feedforward guidance), but also showing results for the SoHF for reference.

A. Human Driver Model

The human driver is modeled according to the extended Van Paassen (VP) driver model [3], which was found to be suitable for generating personalized reference trajectories [10]. A block diagram of this driver model is shown in Fig. 2, where all model parameters that can be manipulated to change the modeled driver steering behavior are shown in red. The model uses the road curvature at a look ahead time τ_{LH} , filtered with a second-order low-pass filter (constant T_{hs}), as the input. A driver feedforward gain K_{FF} is then applied together with scaling terms for the vehicle steering system (steering wheel stiffness K_w , wheel base L_{wb} , vehicle speed V and effective steering ratio K_{eff}). The lateral error with respect to the curve cutting reference is computed at the prediction time τ_p , and scaled by the driver feedback

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gain K_{FB} . The combined signal is sent through a first-order human neuromuscular dynamics transfer function that produces a steering wheel angle, δ_s .

The vehicle dynamics are described by a simplified linear bicycle model [11], with the road curvature κ at the vehicle location and the steering angle δ_s as inputs. The state vector includes the side slip angle β , yaw rate r , heading angle ψ_L and lateral offset from the road centerline s_{lat} . The coefficients in (1) are defined according to (2)-(7); V is the longitudinal speed and l_s is the look-ahead distance of the bicycle model. Table I provides an overview of the parameter settings for the driver model [3] and vehicle dynamics [11].

$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \\ \dot{\psi}_L \\ \dot{s}_{lat} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{21} & 0 & 0 \\ a_{12} & a_{22} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ V & l_s & V & 0 \end{bmatrix} \begin{bmatrix} \beta \\ r \\ \psi_L \\ s_{lat} \end{bmatrix} + \begin{bmatrix} 0 & a_{15} \\ 0 & a_{25} \\ -V & 0 \\ -l_s V & 0 \end{bmatrix} \begin{bmatrix} \kappa \\ \delta_s \end{bmatrix} \quad (1)$$

$$a_{11} = -\frac{2(c_f + c_r)}{MV} \quad (2) \quad a_{12} = \frac{2(c_r l_r + c_f l_f)}{MV^2} - 1 \quad (3)$$

$$a_{15} = \frac{2c_f}{MVR_s} \quad (4) \quad a_{21} = \frac{2(c_r l_r - c_f l_f)}{I_Z} \quad (5)$$

$$a_{22} = -\frac{2(c_r l_r^2 + c_f l_f^2)}{I_Z V} \quad (6) \quad a_{25} = \frac{2c_f l_f}{I_Z R_s} \quad (7)$$

TABLE I: Driver model and vehicle dynamics parameters.

c_f	front cornering stiffness	65000 [N/rad]
c_r	rear cornering stiffness	57000 [N/rad]
I_Z	yaw moment of inertia	1810 [kg·m ²]
K_δ	human curve negotiation parameter	$1.25/K_w$ [rad/Nm]
K_{eff}	effective steering ratio	1/15 [-]
K_w	steering wheel stiffness VP model	1 [Nm/rad]
l_f	front axle distance	1.127 [m]
l_r	rear axle distance	1.485 [m]
l_s	look ahead distance	5 [m]
L_{wb}	wheelbase length	2.8 [m]
M	vehicle mass	1476 [kg]
R_s	steering gear ratio	16 [-]
V	longitudinal vehicle velocity	22.22 [m/s]

B. Extending the Van Paassen Model with Prepositioning

To obtain more representative human-like driver behavior from the VP model, an extension first derived by Barendswaard [7] was implemented. This extension enables pre-corner positioning and early corner steering behavior.

TABLE II: Van Paassen model baseline parameter set for preliminary simulations.

K_{FF}	K_{FB}	$T_{h,s}$	τ_{LH}	τ_p
0.21 [-]	0.07 [-]	0.45 [s]	1.5 [s]	1.3 [s]

Table II lists the baseline values that were used in these simulations for the Van Paassen model parameters. Additionally, an outer pre-positioning driver class (as was categorized in [7]) is selected with zero straight section bias. This produces a small amount of pre-positioning towards the outside of the curve. This parameter set was found to produce a moderate amount of curve cutting for a curved road section with a road radius of 205 m at a speed of 80 kph, see [9].

C. FDCA Shared Control Simulation

After establishing a baseline driving trajectory representative for a human driver, this can be used as the HCR in the complete FDCA shared control simulation. This next simulation consists of a human controller based on the extended Van Paassen driver model and a haptic controller based on the FDCA, which generates a steering torque from the HCR reference.

The haptic controller includes a feedforward component that scales the steering angle from the HCR reference by the *Level of Haptic Support* (LoHS), see Fig. 1. Additionally, a feedback component combines heading (gain $K_\psi = 2$ Nm/rad) and lateral (gain $K_s = 0.1$ N) errors and scales the sum of these by the *Strength of Haptic Feedback* (SoHF). Before the feedforward steering angle from the LoHS can be combined with the feedback torque it needs to be converted to a torque, using an approximation developed by Ghys [8], which uses two successive numerical differentiations of the steering angle, using filters with a 0.05 s time constant.

In the simulations, the output torques of the human and haptic controller are mixed according to the collaboration gains of the driver and haptic controller, K_{Driver} and K_{FDCA} . The scaling of these torque contributions is given by (8), with the sum of these gains adding up to 1.

$$T_{total} = K_{FDCA} \cdot T_{FDCA} + K_{Driver} \cdot T_{Driver} \quad (8)$$

The haptic (FDCA) controller collaboration gain was set to a value of 0.63, while the human driver gain was set to 0.37, in line with previous research on this topic [8]. The neuromuscular system (NMS) and steering wheel (SW) mechanical properties were lumped into a single second-order system, with combined inertia, damping and stiffness as listed in Table III.

TABLE III: Baseline values for steering wheel and neuromuscular mechanical properties.

	J	B	K
SW	0.005 [kg·m ²]	0.03 [Nms/rad]	1 [Nm/rad]
NMS	0.064 [kg·m ²]	0.1 [Nms/rad]	1 [Nm/rad]
Total	0.069 [kg·m ²]	0.13 [Nms/rad]	2 [Nm/rad]

The final FDCA design parameter, the *Level of Haptic Authority* (LoHA) effectively sets the authority level of the haptic support by adjusting the stiffness of the steering wheel. Changing the LoHA will shift the control authority balance between a human driver and the haptic support, and drivers will adapt to such a change [3]. The LoHA is not further considered as a free design parameter in this paper, please refer to [9] for more details.

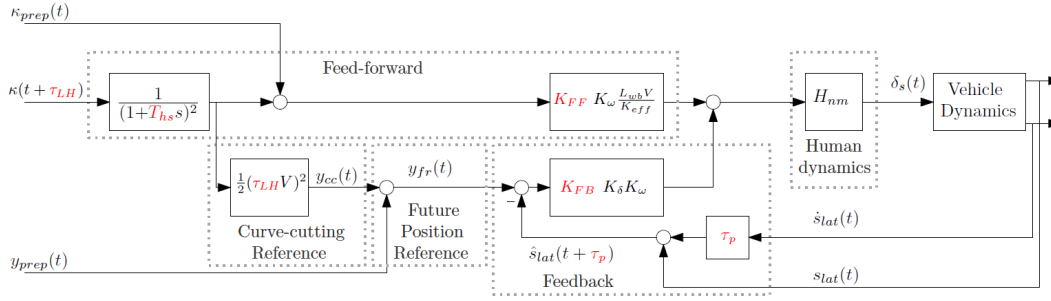


Fig. 2: Block diagram of the extended Van Paassen driver model [7].

D. FDCA Parameter Sensitivity

From the simulations, the sensitivity to variations in LoHS and SoHF is determined by varying the FDCA parameters one by one, while keeping other parameters constant. The torque conflict, mean human torque contribution, human steering effort and lateral performance are used as sensitivity metrics. The torque conflict is computed according to (9).

$$T_{conf} = \begin{cases} |T_{Driver} - T_{FDCA}| & \text{if } T_{Driver} \cdot T_{FDCA} < 0 \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

The average of all torque conflicts and the time percentage for which there is conflict are reported. The human torque contribution T_h is computed as the median of the human torque fraction of the total torque for the complete time series. Furthermore, the HSC performance is determined by the average of the lateral position error (e_{lat}) with respect to the HCR trajectory. Finally, the human work done W_h in a run is computed by integrating the product of human torque and steering wheel rate.

1) *LoHS Sensitivity*: The *Level of Haptic Support*, i.e., the intensity of the supplied feedforward guidance, is varied in steps of 0.2 from 0.4 (low haptic support) to 1.0 (full haptic support). The resulting lateral trajectories can be seen in Fig. 3. As expected, a full feedforward gain of the steering angle ($K_{LoHS} = 1$) causes the shared control system to exactly follow the haptic reference (HCR). As the level of haptic support is reduced, the model exhibits less curve cutting. Increasing the LoHS reduces the amount of torque conflict, increases lateral steering performance and requires lower human torque contributions, see Table IV.

2) *SoHF Sensitivity*: The *Strength of Haptic Feedback*, i.e., the intensity of provided feedback corrections in the FDCA, is varied from 0.5 (low feedback) to 1.5 (strong feedback) at a LoHS fixed at 0.7 so that differences between SoHF levels can be better observed. The resulting lateral trajectories are shown in Fig. 4. It is clear that even if the SoHF is increased, it cannot make up for an incomplete LoHS. The simulations indicate there is no need for increasing the SoHF past intermediate values of around 1.2. The metrics in Table V show a decrease in conflict as SoHF is increased. This, however, assumes that the human driver would accept the unnatural curve driving behavior, which contrasts with results from literature and previous

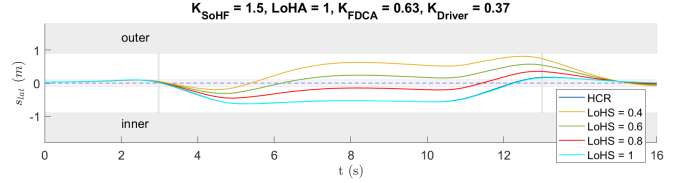


Fig. 3: Level of Haptic Support (LoHS) lateral position sensitivity.

TABLE IV: Resulting metrics for LoHS simulations.

LoHS	T_{conf} Nm	T_h	e_{lat} m (μ/σ)	W_h Nm
0.4	0.062 (1.4%)	0.521	0.548/0.464	0.920
0.6	0.056 (1.1%)	0.471	0.364/0.308	0.801
0.8	0.033 (0.8%)	0.422	0.181/0.153	0.690
1	0.013 (0.9%)	0.370	0.005/0.007	0.590

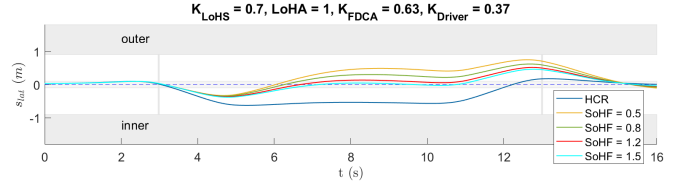


Fig. 4: Strength of Haptic Feedback (SoHF) lateral position sensitivity.

TABLE V: Resulting metrics for SoHF simulations.

SoHF	T_{conf} Nm	T_h	e_{lat} m (μ/σ)	W_h Nm
0.5	0.0910 (2.0%)	0.527	0.464/0.403	0.848
0.8	0.0773 (1.6%)	0.498	0.384/0.330	0.806
1.2	0.0631 (1.2%)	0.471	0.311/0.265	0.765
1.5	0.0447 (1.1%)	0.462	0.273/0.231	0.744

experiments [8]. The HSC model is thus not suitable for making realistic predictions on the amount of torque conflict and driver acceptance across different SoHF settings.

E. Simulation Results and Observations

From these simulations it is found that the LoHS setting has a strong effect on the trajectory that is driven. As the LoHS reduces, the steering feedforward becomes increasingly incomplete. As a result, the vehicle trajectory in the curve goes from curve cutting at high LoHS values (> 0.75) to more sloppy curve negotiation where the curve is driven closer to the outer edge at intermediate LoHS values (0.4-0.6). As long as the human and haptic references match, increasing the LoHS reduces the amount of torque conflict while improving lateral steering performance. Furthermore,

the necessary human steering torque decreases significantly as the LoHS is increased. Due to the strong effects of the selected LoHS on the vehicle trajectory, the conflict, and the required human steering effort, it should be considered as the first and most crucial parameter to tune once an HCR has been established for the FDCA.

Increasing the SoHF from a low to intermediate value provides a significant increase towards matching the reference steering performance, whereas an increase in SoHF from intermediate to high only adds a further small increase in performance. It is concluded that this HSC model is not suitable for making realistic predictions on the amount of torque conflict across SoHF settings. However, it remains important to prevent jerky steering feedback that can be perceived as obtrusive. Therefore, instead of focusing on the SoHF setting it is deemed more beneficial to find a good setting for the LoHS for a realistic HCR, which then requires only a weak feedback contribution (i.e., low SoHF).

While the presented results focus exclusively on a perfectly matched HCR and driver, this is not always a realistic assumption. Hence, [9] includes additional results where two ‘worst-case’ HCR misalignments are studied: a strong curve cutting reference combined with normal curve cutting and a normal curve cutting reference with anti-curve cutting [10]. It is found that an overly strong curve cutting reference is nearly as bad as one that is too weak. Therefore, a reference with a conservative amount of curve cutting should, in general, be implemented.

III. EXPERIMENT

Based on the results from the simulations, the effect of LoHS was further investigated in a haptic shared control experiment with human participants. A previous study tested two LoHS values, 0.5 and 0.92 [8]. To get more insight with regards to the influence of this parameter on conflict torque occurrence and driver acceptance, the current experiment varied the LoHS between 0, 0.25, 0.50, 0.75, 0.92 and 1.0. This is also in line with the study by Mars et al. [12], which provides a good candidate for comparing findings, even though their HSC system is not based on the FDCA. The SoHF is fixed at 1.5 and a unity LoHA setting is used (reference steering wheel stiffness). The HCR is generated with the VP model using the parameters from Table II and exhibits moderate curve-cutting without prepositioning.

A. Apparatus

A fixed-base car simulator at the HMI-Lab at the Aerospace Engineering faculty of Delft University of Technology was used for the experiment. The car controls include a control-loaded steering wheel. For this experiment, the gas and brake pedals are not used as the vehicle speed is kept fixed at 80 kph. The outside view is projected on three screens with a horizontal field of view of 180 degrees and a vertical field of view of 40 degrees. The vehicle in the simulation is a sedan with a 1.8 m width and simplified vehicle dynamics [7], [8], [13]–[15]. Fig. 5 shows a picture of the experiment setup, as seen from behind the driver seat.

B. Haptic Shared Control Implementation

A haptic controller implementation based upon the FDCA was implemented in the driving simulator. The lateral position and heading feedback gains K_s and K_ψ were set to 0.08 and -0.03, respectively. To account for modeling differences in the steering wheel dynamics, the steering wheel properties were identified in a separate procedure and used to update the HSC, see [9] for details.

C. Driving Task and Road

The control task consists of steering the simulated vehicle along a winding road with six left and six right clothoidal corners with a curve radius of 205 m at a speed of 80 kph [8]. The steering required in the curves is close to the upper limit for the allowed lateral acceleration for road design rules [13]. The road consists of a single lane with clearly marked road edges and a road width of 3.2 m. A straight section of 240 m was included in between turns.

D. Experiment Design

The manual driving condition is used as a baseline to compare the shared control conditions to and is achieved in the experiment by setting the LoHS and SoHF equal to zero. The experiment is conducted according to a within-subjects design with six conditions where the only independent variable is the LoHS. A balanced Latin square design is used to reduce the potential for detrimental effects related to learning, carry-over and fatigue.

Before the start of the first run every subject performed one training run in the manual driving condition and one training run at a LoHS of 0.5 to familiarize with the driving simulator and the HSC. The driving task can be learned quickly, as only steering input on the steering wheel is required.

E. Participants and Instructions

Eighteen participants were recruited (6 female) with ages ranging between 22 and 57 years. The experiment plan was approved by the Human Research Ethics Committee of Delft University of Technology (application 1751).



Fig. 5: Car simulation setup in the HMI-Lab fixed-base driving simulator.

F. Dependent Measures and Metrics

Throughout every experiment run data were collected in real time. The objective data consist of vehicle and environment states, steering wheel parameters and torque data. The experimentally measured torque conflict is defined as:

$$O_{\text{conflict}} = \begin{cases} 1, & \text{if } T_{\text{Driver}} \cdot T_{\text{FDCA}} < 0 \\ & \text{and } |T_{\text{Driver}}| > 0.1 \cdot \max|T_{\text{FDCA}}| \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

When a conflict occurs, the conflict torque is defined as the absolute value of the difference between driver and haptic support torques. A total conflict magnitude is obtained by integrating this conflict over time. Driver steering effort (SEf) [6] is computed by integrating the squared driver torque over time for each run of the experiment. This metric gives an indication of the amount of effort that is required by the human driver to complete the steering task. The steering wheel reversal rate (SWRR), the number of steering wheel reversals per unit of time, is calculated using the procedures outlined in [16], [17]. Finally, the standard deviation of lateral position (SDLP) is computed as an indicator for the amount of lateral swerving along the road for each condition.

After each experiment run with haptic feedback (i.e., not for the manual driving condition), a Van der Laan questionnaire was used to obtain subjective ‘satisfaction’ and ‘usefulness’ scores for each LoHS setting [18].

G. Hypotheses

Three main hypotheses were defined for the haptic shared control driving simulator experiment regarding HSC acceptance and the effect of varying the LoHS. Higher levels of support (increased LoHS) are expected to be subjectively preferred (hypothesis I) and result in reduced driver steering effort, steering wheel reversal rate, and torque conflicts (hypothesis II). Finally, also lateral steering performance in terms of the SDLP is expected to improve with increasing LoHS (hypothesis III).

IV. RESULTS

A. Subjective Data

The median and interquartile range of the ‘usefulness’ and ‘satisfaction’ scores that were computed from the Van der Laan questionnaire data are shown in Fig. 6 for every experimental condition. A clear trend can be observed towards the higher LoHS settings, which are rated as more useful and satisfactory. Friedman tests reveal a significant effect of the LoHS on both the satisfaction ($\chi^2(4) = 28.7, p < 0.05$) and usefulness scores ($\chi^2(4) = 23.0, p < 0.05$).

B. Objective Data

The objective data contains information regarding the torque conflict, steering effort, steering wheel reversal rate and lateral position (Fig. 7). Torque conflict reduces with increasing LoHS and is decreased by 70% for the highest

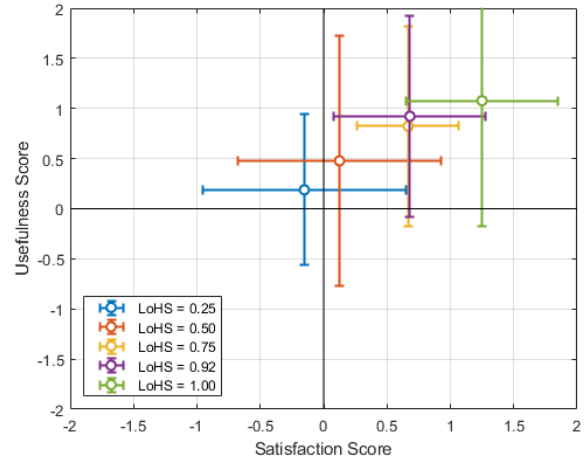


Fig. 6: Van der Laan usefulness and satisfaction scores.

tested LoHS values compared to low LoHS settings. A one-way ANOVA confirms a significant effect of LoHS on the conflict magnitude, $F(1, 1.905) = 54.3, p < 0.05$. Steering effort is likewise reduced with increasing LoHS, an up to 81% reduction compared to the manual driving condition. However, for the low LoHS setting of 0.25, steering effort is higher than in the manual driving condition (a significant effect, $p = 0.012$), indicating a lack of benefit at low LoHS settings. SWRR values significantly decrease with increasing LoHS (Friedman test, $\chi^2(5) = 42.997, p < 0.05$), showing a significant difference with unsupported driving at all levels. Finally, the SDLP decreases by approximately 20% for all haptic conditions compared to the manual driving condition, but shows no clear difference between the haptic support conditions. This difference in SDLP between manual and shared control conditions is also significant; Friedman test, $\chi^2(5) = 31.7, p < 0.05$.

V. DISCUSSION/CONCLUSIONS

The presented simulation model analysis explored the effects of tuning different settings of the FCDA, under the assumption that the human operator behavior would not adapt to the tuning. This indicated that an increased haptic feedback strength (higher SoHF) does not result in improved HSC performance, while introducing the risk for a lower acceptance, as can be expected from increased torque conflict. Additionally, various levels of haptic support (LoHS) were seen to result in distinctly different types of cornering behavior.

In a human-in-the-loop driving simulator experiment, the adaptation to LoHS was further investigated. The adaptation is indeed effective, resulting in similar steering task performance for all levels of haptic support. With the given heuristic tuning of haptic feedback (SoHF), authority (LoHA) and a moderate corner cutting reference (HCR), it appears that high levels of support (LoHS = 0.7 to 1.0) are subjectively preferred, confirming our hypothesis I. Furthermore, an increased LoHS results in significantly reduced torque

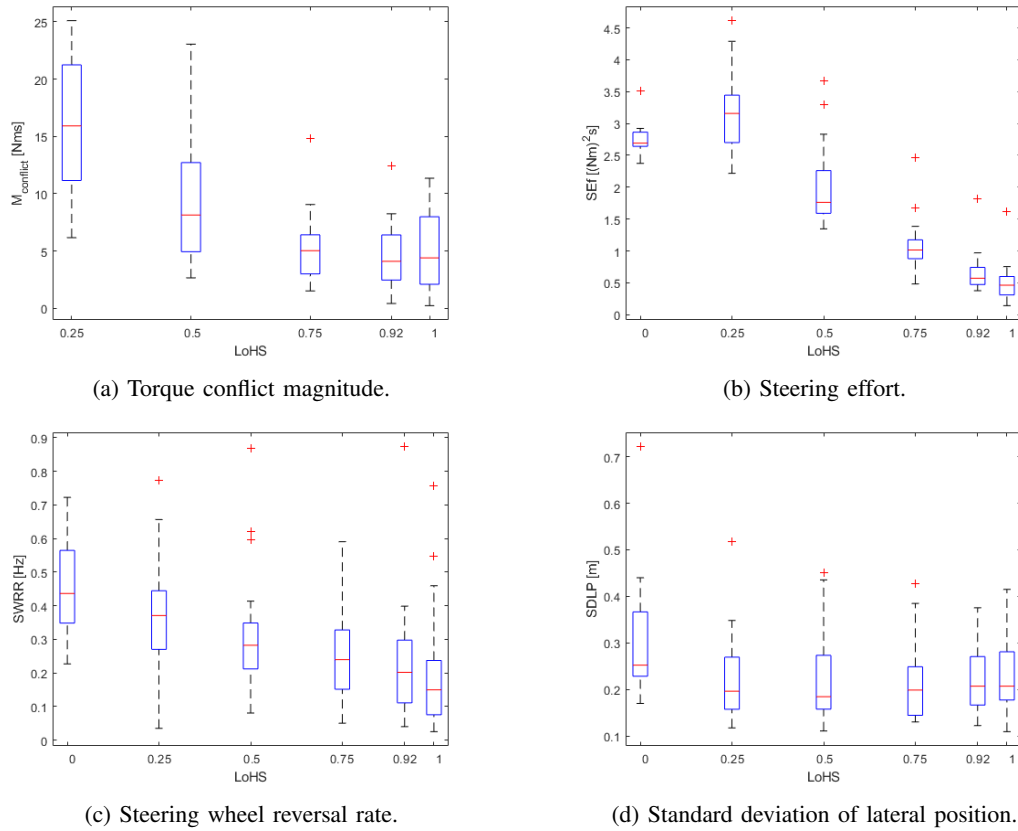


Fig. 7: Objective driving metrics for different LoHS, with manual driving reference data for SEf, SWRR, and SLDP.

conflict (70%), steering effort (81%), and steering reversal rate; as a result, hypothesis II is accepted. Finally, contrary to hypothesis III, lateral deviation errors are 20% lower with an active HSC, irrespective of the LoHS setting. Overall, the results thus indicate that a high LoHS (strong feedforward guidance) improves HSC performance for car steering.

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