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Haptic shared steering control with an adaptive level of authority based on time-to-line crossing ⋆

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Abstract: Traditional driver-automation interaction trades control over the vehicle back and forth between driver and automation. Haptic shared control offers an alternative by continuously sharing the control through torques on the steering wheel and pedals. When designing additional feedback torques, part of the design choice lies in the stiffness around the neutral steering point: also called the Level of Haptic Authority (LoHA), which is usually static and tuned to balance safety benefits (better at high LoHA) with conflicts torques in case of different intentions between automation and driver (higher conflict torques with increased LoHA).In this paper we explore the idea of situation-adaptive LoHA: in this case during lane-keeping by changing the LoHA based on time to lane crossing (TLC). Consequently, when safety margins are high (e.g., when driving on a wide road) the LoHA is low, but the LoHA would only increase when safety margins decrease. We propose two alternative design approaches to apply the LoHA: symmetrically and asymmetrically (i.e., only increase of LoHA in the direction of the low TLC). We compared these design in an explorative driving simulator study (n=14) to driving with two static LoHA designs (low and high).We found that compared to the high LoHA controller, both adaptive LoHA controllers designs resulted in similar safety margins, but at decreased conflict torques. Hence, a TLC-based adaptive LoHA controller seems to be an effective approach to mitigate conflicts while maintaining the safety benefits associated with HSC.

Keywords: Haptic Shared Control, Adaptive, Level of Haptic Authority, Human-Machine interaction, driving simulator.

1. INTRODUCTION

Haptic Shared Control (*HSC*) implements the control action of an autonomous driving system through the steering wheel, in which the driver and the vehicle communicate continuously through forces on the steering wheel (Abbink et al., 2012). By keeping the driver actively engaged in the control loop, the interactions mitigates the “pitfalls of automation” related to supervised autonomous driving (Flemisch et al., 2008) while benefiting from an increased driving performance (Forsyth and MacLean, 2006) and reduced workload.

One approach to achieve HSC is to combine force and stiffness feedback. More specifically, a torque that turns the steering wheel towards the desired steering wheel angle and an added stiffness through a virtual spring around that steering wheel angle (Abbink and Mulder, 2009). This artificial stiffness around the controller's desired steering angle and is called the Level of Haptic Authority (LoHA). The stiffer the LoHA is, the harder it becomes to deviate from the controller's actions and vice versa. Consequently, driver and controller can negotiate, by adjusting their stiffness (co-contraction and LoHA, resp.), whose desired steering wheel angle is realized (Abbink et al., 2012).

Generally, higher LoHA controllers yield the better performance improvements in terms of lateral position, safety margins and variability (Mars et al., 2014; Petermeijer et al., 2014), but can result in forceful corrections, as drivers typically exhibit satisficing instead of optimizing behaviour (Goodrich et al., 2000; Boer, 2016). During such conflicts, drivers need to ‘fight’ the controller to overcome the generated steering wheel torques, resulting in lower user acceptance and an increased chance of disuse (De Winter and Dodou, 2011). This is probably the reason that low LoHA controllers are preferred by drivers.

Tuning the LoHA is thus a trade-off between performance benefits and driver acceptance. Though, an alternative solution is to implement an adaptive LoHA, which assists the driver when needed. As such, adaptive LoHA based on lateral error, with respect to a centerline reference trajectory, has been implemented by Abbink and Mulder (2009). They found a negative effect on control effort, as the controller inflated conflict torques between driver and reference and did not allow for satisficing driver

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behaviour. Instead, an adaptive controller should reduce the size of trivial conflicts, when the driver is safe, by reducing the LoHA; whilst providing strict support, in critical situations by increasing the LoHA.

Satisficing behaviour in driving is based on the assumption that drivers want do not want to exceed a certain safety margin and perception of risk (Gibson and Crooks, 1938); an intuitive way to interpret safety margins is through the Time to Lane Crossing (TLC; Godthelp, 1988), which captures a combination of risk related factors in a single value, namely velocity, road width, curvature, lateral position, and heading.

In this study we present a novel haptic shared controller, that adapts the LoHA based on TLC. First, the mathematical implementation of LoHA in a Haptic Shared Controller will be presented. Second, the LoHA's effect on the perceived steering wheel torques in case of a disagreement between driver and controller will be analysed. Third, design of the adaptive LoHA algorithms, based on the TLC, will be explained. Finally, the preliminary results of a human-in-the-loop simulator study will be presented to evaluate if the controller operated as expected.

1.1 Four Design Choice Architecture

The Four Design Choice Architecture (FDCA; Van Paassen et al., 2017), was used to implement a LoHA based on TLC. Compared to previously used haptic shared controllers (Mulder et al., 2008), the FDCA separates the feedforward and feedback torques, which allows them to be independently tuned. The FDCA controller consists of the following four components (see Figure 1):

- Human Compatible Reference (*HCR*): The predetermined reference trajectory for the road.
- Level of Haptic Support *(LoHS)*: The feedforward percentage of torques required to follow the HCR.
- Strength of Haptic Feedback (*SoHF*): The feedback gains that correct deviations from the HCR.
- Level of Haptic Authority (*LoHA*): A virtual spring around the controller's desired steering wheel angle.

Human Compatible Reference The Human Compatible Reference (HCR) is the trajectory that the automatic controller tries to follow. The HCR was generated a priori, as in Scholtens et al. (2018), and consists of a trajectory (i.e., lateral position and heading on the road) and the steering wheel angles required to follow that trajectory.

Steering Wheel Dynamics The steering wheel is modelled as a simple mass-spring damper system, with steering wheel angle (θ), steering wheel torque (τ), inertia (I_{sw}), damping (B_{sw}), and stiffness (K_{sw}).

$$\ddot{\theta} = \frac{1}{I_{sw}}\left(\tau - B_{sw}\dot{\theta} - K_{sw}\theta\right) \tag{1}$$

A Laplace transformation is applied to obtain the transfer function (Eq. 2) of the steering wheel dynamics.

$$H_{sw}(s) = \frac{1}{I_{sw}\cdot s^2 + B_{sw}\cdot s + K_{sw}} \tag{2}$$

Through inversion a transfer function of the inverse steering wheel dynamics is obtained. Because this equation is improper, a second order Butterworth filter is added (Eq. 3). The filter's cut-off frequency (ω_c) is set at 3 Hz, the natural cut-off frequency of the human response (Van der Helm et al., 2002).

$$H_{butw}(s) = \frac{1}{(\frac{s}{\omega_c})^2 - (\lambda_1+\lambda_2)\frac{s}{\omega_c} + \lambda_1\lambda_2} \tag{3}$$

$$H_{sw}^{-1}(s) = \frac{I_{sw}\cdot s^2 + B_{sw}\cdot s + K_{sw}}{(\frac{s}{\omega_c})^2 - (\lambda_1+\lambda_2)\frac{s}{\omega_c} + \lambda_1\lambda_2} \tag{4}$$

$$\lambda_{k(1,2)} = e^{\frac{i\pi}{2n}(2k-1+n)} \tag{5}$$

Level of Haptic Support The LoHS is essentially the percentage of the feedforward steering action that is being performed by the controller (Van Paassen et al., 2017). At 0% the controller has no feedforward component and acts only on the feedback controller, at 100% the controller performs all feedforward steering actions which means that without disturbances it will follow the HCR and basically act like a fully autonomous car. The feedforward torque (τ_{FF}) required to generate the steering wheel angles is given in Eq. 6, with steering wheel angle (θ_{HCR}), percentage of LoHS (λ_{LoHS}), and inverse steering dynamics (H_{sw}^{-1}).

$$\tau_{FF} = \lambda_{LoHS}\cdot\tau_{hcr} \tag{6}$$

$$= \lambda_{LoHS}\cdot H_{sw}^{-1}\cdot\theta_{HCR} \tag{7}$$

Strength of Haptic Feedback The Strength of Haptic Feedback (SoHF) is the gain with which the controller corrects deviations from the vehcile with respect to the HCR. The lateral and heading devation (Δ_y and Δ_ψ, resp.) with their respective gains (K_y and K_ψ), divided by the inherent steering wheel stiffness (K_{sw}), determine the feedback steering wheel angle (θ_{FB}). In order to obtain the required feedback steering wheel torque, the steering angle is multiplied by the inverse steering wheel stiffness as in Eq. 9.

$$\theta_{FB} = \frac{K_y\cdot\Delta_y + K_\psi\cdot\Delta_\psi}{K_{sw}} \tag{8}$$

$$\tau_{FB} = H_{sw}^{-1}\cdot\theta_{FB} \tag{9}$$

Level of Haptic Authority The LoHA determines how forceful the controller will exert the feedback and feedforward torque. Mechanically it acts like a virtual spring on the steering wheel around the desired steering wheel angle of the FDCA controller. The LoHA (K_{LoHA}) is decomposed into the inherent steering wheel stiffness (K_{sw}) and an added stiffness (K_{added}). Torque calculation is given in Eq. 11, as a function of the inverse steering wheel dynamics (H_{sw}^{-1}),the added stiffness (K_{added}), the second-order butterworth filter (H_{filt}), the current steering wheel angle (θ_{sw}), and the combined desired feedback and HCR steering angle (i.e., $\theta_{co} = \theta_{FB} + \theta_{HCR}$).

$$K_{LoHA} = K_{sw} + K_{added} \tag{10}$$

$$\tau_{LoHA} = (\theta_{co} - \theta_{sw})\cdot\left(H_{sw}^{-1} + \frac{K_{added}}{H_{filt}}\right) \tag{11}$$

Consequently, the torque the driver needs to exert on the steering wheel to follow the HCR is independent of the chosen LoHA.

The total haptic share control torque (τ_{HSC}) is obtained by adding up the feedforward torque (τ_{FF}: Eq. 7), feedback torque (τ_{FB}; Eq. 9), and (τ_{LoHA}; Eq. 11) as in Eq. 13.

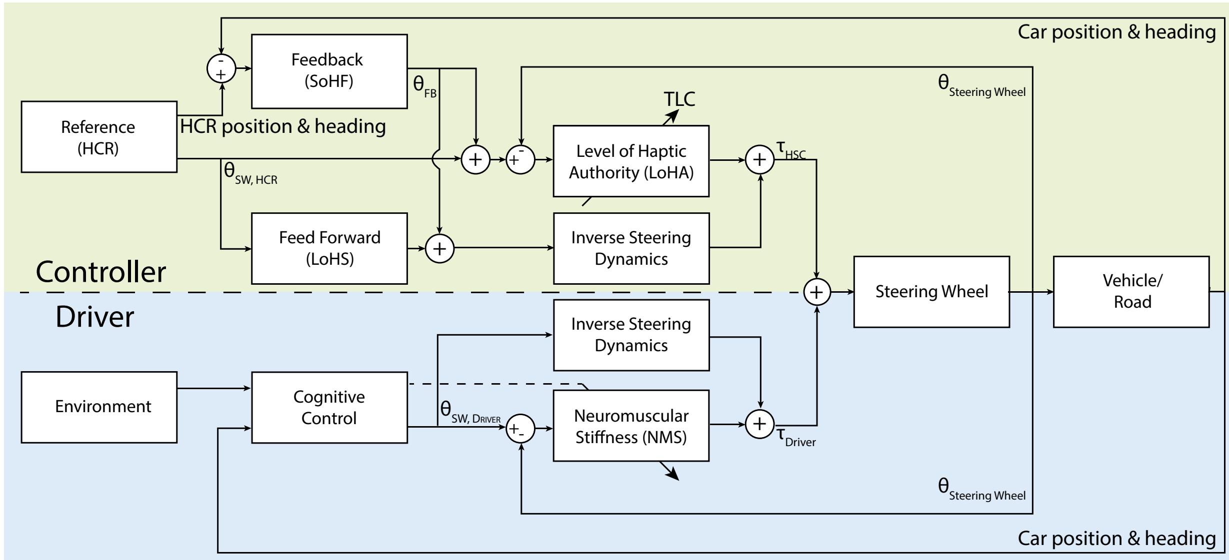

Fig. 1. A block scheme of the FDCA-controller (top, green) and the driver (bottom, blue) in a haptic shared steering control system. Note the four design components, namely the Human Compatible Reference (HCR), Level of Haptic Support (LoHS), Strength of Haptic Feedback (SoHF), and Level of Haptic Authority (LoHA).

$$\tau_{HSC} = \tau_{FF} + \tau_{FB} + \tau_{LoHA} \tag{12}$$

$$\tau_{HSC} = \lambda_{LoHS} \cdot H_{sw}^{-1} \cdot \theta_{HCR} + H_{sw}^{-1} \cdot \theta_{FB}... \\ ... + (\theta_{HCR} + \theta_{FB} - \theta_{sw}) \cdot \left(H_{sw}^{-1} + \frac{K_{added}}{H_{filt}} \right) \tag{13}$$

1.2 Simulation of LoHA controller

To evaluate the effect of LoHA and LoHS on the steering wheel angle, controller torques, and driver torques a simulation of their behaviour is performed.In the simulation both the controller and driver make the exact same steering movement but the human command is delayed by five seconds, this results in consecutive sections of conflict and agreement between the controller and the driver. Note that this simulation the desired steering angles of driver and controller are a-priori defined, hence it essentially simulates feedforward torques and does not take feedback into account.

The driver's dynamics are simulated by a separate mass-spring-damper system. In order to evaluate the contribution of each actor (i.e., driver and controller) fairly, the driver's inertia and dampening are chosen the same as those of the steering wheel. The controller has no estimates of the human inertia, dampening or stiffness while the human model does anticipate the steering wheel's inertia and dampening because of system identification naturally performed by humans (Kawato, 1999). The resulting steering wheel angle and torque responses can be observed in Fig. 2 and Fig. 3

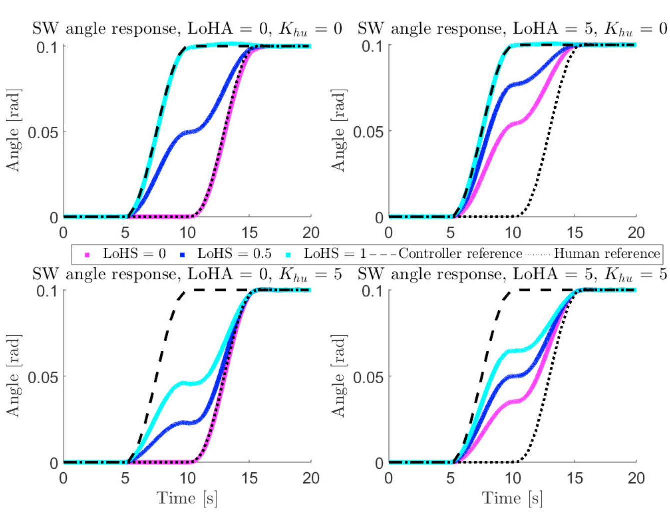

Fig. 2. Steering angle response during a conflict for different ratios of LoHS, LoHA and driver stiffness. The black dashed line represents the driver's steering angle, the dash-dot line represents the controller's angle.

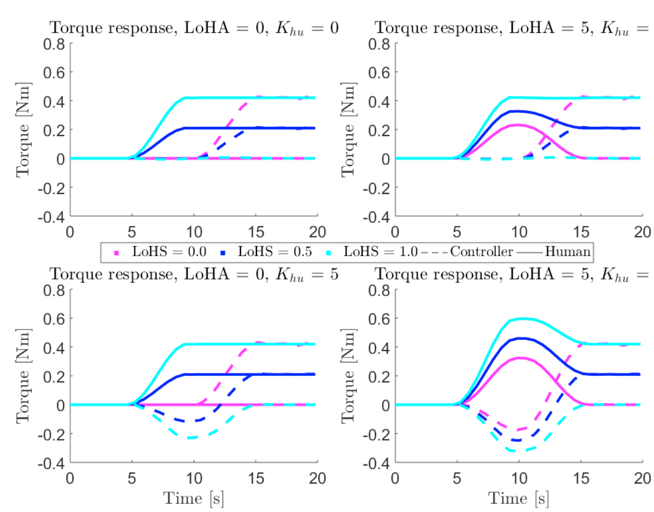

Fig. 3. Driver and controller torque responses during a conflict for different ratios of LoHS, LoHA and driver stiffness. The solid lines represent the controller torque. The dashed lines represent the driver torque.

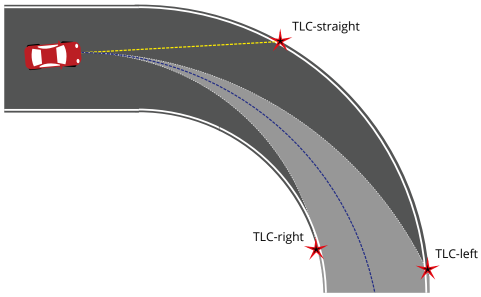

Fig. 4. Illustration of three different TLC calculations: Yellow - extrapolation of vehicle heading ; Blue - extrapolation of yaw rate ; White - yaw uncertainty swath. The latter is used in this research.

The following observations are made during conflicting steering angles: LoHA is an effective way to shift the resulting steering wheel angle towards the controller's desired angle (LoHA = 5; Fig. 2, right plots). However, if the driver compensates his own stiffness (Human stiffness: K_{hu}) this effect on the steering wheel angle is mitigated ($K_{hu} = 5$; Fig. 2, bottom plots) while the conflicting torques increase (dashed lines; bottom Fig. 3).

When the LoHS is one and the LoHA is zero, the controller's desired steering angle is followed (i.e. blue and dashed line are identical). Vice versa, when the LoHS is zero the implemented steering angle is identical to that of the desired steering angle of the driver.

When driver and controller agree, the LoHA has no effect on either the steering angle or the torques; in this case the LoHS fully determines how the torques are divided between the controller and driver. Alternatively, when controller and driver are in conflict the ratio between controller LoHA and driver stiffness (K_{hu}) determine who's desired steering angle will be followed most closely.

These results confirm that the LoHA can be used to shift the steering wheel response between controller and driver during conflicts without affecting torques when they agree. Moreover, the driver is still capable to overrule the controller by adapting their own admittance.

2. ADAPTIVE LEVEL OF HAPTIC AUTHORITY

2.1 TLC calculation

The TLC was calculated as in Boer (2016), which takes into account an uncertainty range of yaw rates and determines a cone-like swath rather than a single TLC value. Consequently, the TLC swath provides directional information about the safety margins around the current trajectory.

2.2 Adaptive LoHA based on TLC

Upper and lower limits LoHA The lower LoHA limit is chosen to 0.0085 (Nm/deg), which is equal to the standard steering wheel stiffness of the simulator's vehicle model (i.e., self-aligning torque during the manual driving). The upper limit at 0.0255 (Nm/deg) was heuristically determined as the highest multiple of the lower limit LoHA before drivers would report dissatisfaction.

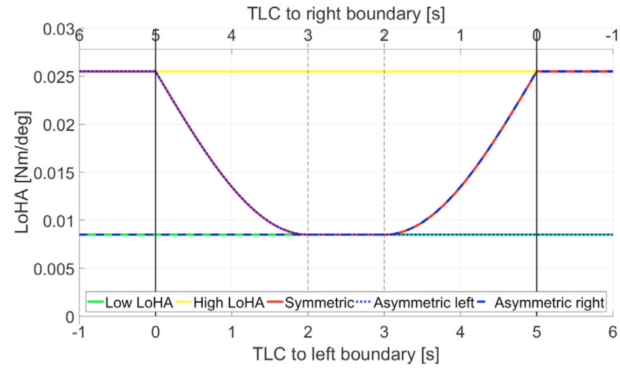

Fig. 5. LoHA profile as a function of the TLC. Note the difference between the asymmetric controller steering left or right.

Upper and lower limits TLC A two second threshold for the adaptive algorithm was based on research by Godthelp (1988) who reported that in straight road driving corrective steering movements are made, on average, at a TLC of approximately 1.3 seconds. Moreover, a two second threshold was also found as the time by which more than 95% of drivers have responded to static roadside stimuli (Triggs and Harris, 1982).

A partial cosine is used to define the relationship between TLC and LoHA to prevent sudden torque pulses on the steering wheel. When ($t_{TLC} \leq 0$), the LoHA reaches its maximum value and does not increase further (i.e., upper limit).

$$K_{LoHA} = \ldots \\ \begin{cases} K_{sw} + K_{add} & , \quad t_{TLC} \leq 0 \\ K_{sw} + K_{add}\left(1 + \cos(t_{TLC} + 2)\dfrac{\pi}{4}\right) & , \; 2 \geq t_{TLC} > 0 \\ K_{sw} & , \quad t_{TLC} > 2 \end{cases} \tag{14}$$

Symmetric and asymmetric LoHA A symmetric implementation of the LoHA (i.e, stiffness around the desired steering wheel angle), shifts authority towards the controller regardless of driver intent and consequently limits the driver to steer into the desired direction. Hence, an asymmetric LoHA was implemented that applies a high stiffness in the direction of the low TLC, but does not apply additional stiffness towards low TLC. Essentially, the asymmetric LoHA restricts the driver to steer towards danger and it allows steering movements to safety.

The same adaptive LoHA profile is used as with adaptive symmetric LoHA but rather than being based on the lowest TLC, the independent value is based on the lowest TLC in the direction of the human torque.

3. SIMULATOR EXPERIMENT

3.1 Method

Participants Fourteen participants voluntarily participated in the driving simulator experiment (5 female, 9 male). The average age was 25.8 years old (SD = 1.8), and participants had their driving license for an average of 6.8 years (SD = 1.7).

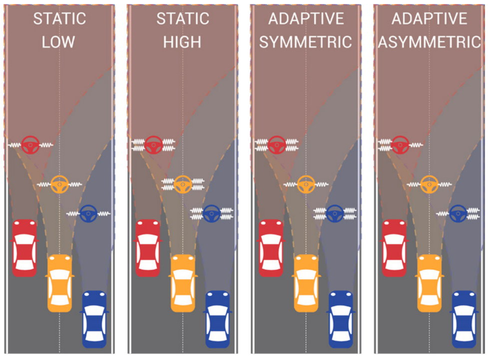

Fig. 6. Visualisation of the steering wheel stiffness of the different LoHA regimes in different road positions. The springs indicate a high or low stiffness for each algorithm in that steering direction, the coloured cones indicate the corresponding TLC swaths.

Table 1. FDCA parameter values used in the experiment for the SoHF, LoHS, and LoHA

K_{y-SoHF}	0.3 [Nm/m]
$T_{\psi-SoHF}$	2.0 [Nm/rad]
λ_{LoHS}	80 [%]
K_{LoHA}	0.0085 - 0.0255 [Nm/deg]

Apparatus A fixed-based driving simulator at the department of Control and Simulation of the Delft University of Technology was used, which has a horizontal field of view of approximately 180 deg and a vertical view of 40 deg. The steering wheel actuation was done with a MOOG FCS Ecol8000S actuator at 2500 Hz; steering wheel damping: 2 (Nms/rad) and inertia: 0.3 (Nms^2/rad). All data were recorded at a frequency of 100 Hz.

Experimental design & procedure Five different conditions were driven, namely: Manual (M), Low LoHA (L), High LoHA (H), Symmetrical adaptive LoHA (S), and Asymmetrical adaptive LoHA (A).

The road consisted of 16 curves (8 left, 8 right) with radii of 500 m, separated by 150 m straight section to prevent interference between subsequent curve exits and entries. Two road widths (3.6 and 2.2m) were used as an independent factor to manipulate the TLC. Road widths were alternated twice to provide both width transitions: from wide to narrow and narrow to wide. The road had a total length of 7.3 kilometers.

The vehicle's velocity was fixed at 24 (m/s). If the vehicle was outside of the lane boundaries a high frequency disturbance, modelled by a 100 Hz sinewave, was applied on the steering wheel to alert the driver of the lane departure. The controller parameters are listed in Table 1. Participants were instructed to drive as they normally would and stay within the lane boundaries. Each participant drove two training routes, one manual and one with a high stiffness controller, so they experienced both ends of the assistance spectrum prior to the experimental trials. Next, the experimental trials were driven in a randomised order to mitigate any learning effects

3.2 Results

Fig. 7 shows the time traces of one participant for the symmetric and assymetric controller, to visualize the controller design. In the wide section of the road (2000-2500 m) the TLC-values is mostly above the 2 second activation threshold, whereas in the narrow section (2500-3000 m) the TLC rarely reaches above 2 seconds. Consequently, in the wide section the LoHA of the controller is mostly equal to the lower limit , whereas in the narrow section it varies between the upper and lower limit. Note the short torque pulses in the narrow section when drivers exceeded the lane boundaries (i.e., TLC = 0). Moreover, in the narrow section the controller torques sometimes change abruptly, due to the erratic nature of the TLC-metric. Subsequent analysis should identify if such abrupt torque changes are disruptive to the driver's steering behaviour and subjective experience of the haptic shared controller.

Fig. 8 shows the mean minimum 10% of the TLC (i.e., indicating of how hazardous the most safety critical situation were) and the mean conflict torques (i.e., opposing torque vectors) between driver and controller. A repeated measures ANOVA and a pairwise comparison with Bonferroni correction was performed to identify statistical differences. It can be seen that there are no significant differences in terms of TLC-distributions between the controller in the wide nor the narrow sections. Moreover, the High LoHA controller has significantly higher conflict torques compared to the adaptive controllers in the narrow sections.

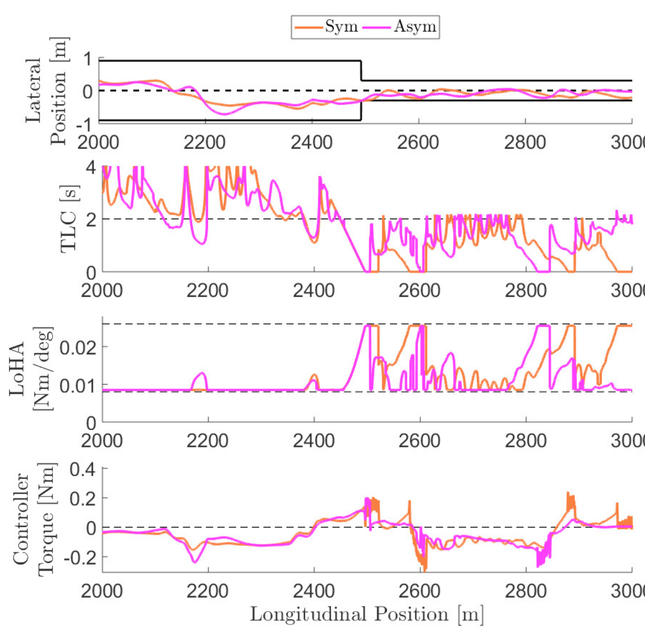

Fig. 7. From top to bottom: Lateral position w.r.t. the centerline, absolute Time to Line Crossing (dashed line: 2 s threshold), Level of Haptic Authority as determined by the controller (dashed lines: upper and lower limit), and the Controller Torque on the steering wheel, of one participant in a wide (2000-2500 m) and narrow (3000-3500 m) road section.

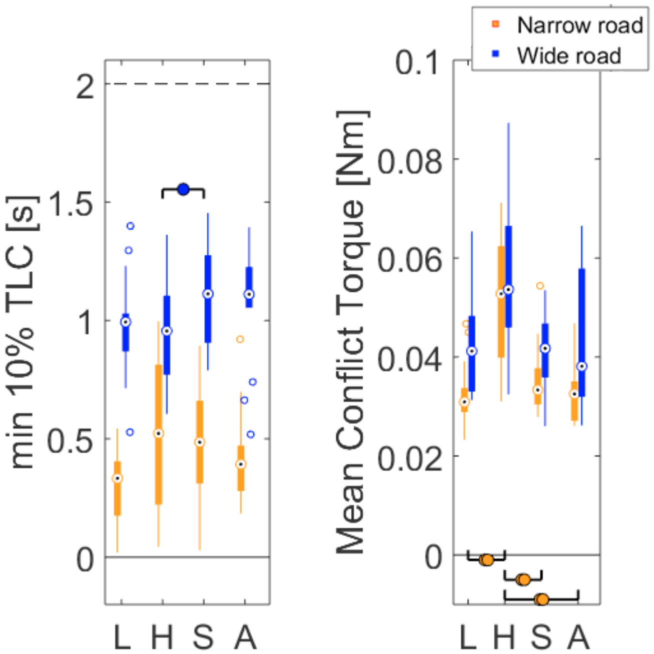

Fig. 8. Boxplot of the mean min 10% TLC (left) and the mean conflict torques (right) across participants per controller (Low, High, Symmetric, Asymmetric) and road width (wide and narrow). ● → p<.05, ●● → p<.01

4. DISCUSSION & CONCLUSION

The goal of this study was to develop an adaptive LoHA algorithm based on TLC that can achieve an increase in safety margins similar to a static high stiffness controller without the drawbacks of high conflicts. An symmetric and asymmetric adaptive Level of Haptic Authority (LoHA) were implemented in the Four Design Choice Architecture, based on a time-to-lane-crossing (TLC) swath.

The preliminary results human-in-the-loop simulator experiment revealed that a TLC-based adaptive controller is a promising approach to shift authority between the driver and controller based on the criticality of the driving situation. The symmetric and asymmetric adaptive controllers yielded decreased conflict torques between driver and controller. Subsequent analysis, should investigate the effect of the controller in terms of steering behaviour, effectiveness, and torque conflicts in more detail.

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