



HAL
open science

Predictive shared steering control for driver override in automated driving: A simulator study

Chunshi Guo, Chouki Sentouh, Jean-Christophe Popieul, Jean-Baptiste Haué

► **To cite this version:**

Chunshi Guo, Chouki Sentouh, Jean-Christophe Popieul, Jean-Baptiste Haué. Predictive shared steering control for driver override in automated driving: A simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2019, 61, pp.326-336. 10.1016/j.trf.2017.12.005 . hal-03642877

HAL Id: hal-03642877

<https://uphf.hal.science/hal-03642877v1>

Submitted on 14 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Predictive shared steering control for driver override in automated driving: A simulator study

Chunshi Guo ^{a,b,*}, Chouki Sentouh ^b, Jean-Christophe Popieul ^b, Jean-Baptiste Haué ^a

^a Technocentre Renault, Cognitive Ergonomics & HMI, 1 avenue du Golf, 78280 Guyancourt, France

^b University of Valenciennes, LAMIH-CNRS UMR 8201, Mont Houy, F-59313 Valenciennes, France

A B S T R A C T

Recent research efforts on automated driving reveal the need to address driver's interaction with vehicle automation. This paper focuses on the design of an override mode for auto-mated driving systems, a topic little studied in literature. In this paper, a shared control framework for driver's override of automatic steering control is proposed. This framework formulates the control transfer between the driver and the system as a constrained opti-mization problem which is solved online by a model predictive controller. At a higher level in the framework, the system detects driver's lane-change intention so that the low-level controller can actively assist the driver in a lane-change maneuver. The whole framework was evaluated in a user test based on a driving simulator. The test results show that the proposed shared control framework has the advantage of allowing the driver to regain con-trol with ease while ensuring the smoothness of control transition.

Keywords:

Automated driving

Shared control

Steering override

Driver-vehicle interaction

1. Introduction

The past few years have witnessed increasing popularity of automated driving (AD) and a rapid advancement of AD technologies. A common view of AD is that an automated system can perform all the driving tasks while the driver is completely disengaged from the controls and monitoring the system. Such a system is classified as a level 4 or 5 system according to the SAE's taxonomy of levels of vehicle automation (SAE, 2016). Despite impressive demonstrations and technical advances, how to ensure the robustness of a level 4 or 5 system in highly complex situations remains an open question (Aeberhard et al., 2015). First generation automated vehicles are more likely to be equipped with level 3 AD systems, i.e., they need to fall back to human drivers in unexpected situations. The system controllability has been emphasized in the recent amendments of the Vienna Convention on Road Traffic which state that the deployment of AD technologies should respect the requirement that they "can be overridden or switched off by the driver" (UNECE, 2016). In this context, driver-vehicle interaction, notably the transfer of control between the driver and the system, constitutes a central issue in the system design.

The "RESPONSE code of practice" for design and evaluation of ADAS (PREVENT., 2009) views driver-vehicle interaction comprising: (1) normal system use within system limits, (2) usage at and beyond exceeding system limits and (3) usage during and after system failures. A large body of research concentrates on the second and the third cases where the system requires the driver to take over control (Strand, Nilsson, Karlsson, & Nilsson, 2014; Blanco et al., 2015; Walch, Lange, Baumann, & Weber, 2015), since these two cases raise human factors issues related to human's out-of-the-loop performance

* Corresponding author at: Technocentre Renault, Cognitive Ergonomics & HMI, 1 avenue du Golf, 78280 Guyancourt, France.
E-mail address: chunshi.c.guo@renault.com (C. Guo).

manifested by, e.g., decreased vigilance and reduced situation awareness (Endsley & Kiris, 1995). A key design issue hence concerns how to design so called “take-over requests”, both in terms of their timing before the system reaches its boundary and their presentation modality (Seppelt & Victor, 2016). In contrast, how to design an override mode in which the driver can initiate the control transfer has not received much attention. Nevertheless, not only is such an override mode required by legal regulations, but also it could influence system’s acceptability and user experience. In a recent online survey on the acceptance of autonomous vehicles in Germany (Wolf, 2016), the possibility of reassuming control of the vehicle at any time is ranked as one of the central user needs.

In previous work on automatic steering control, a traditional scheme for driver steering override is that either the driver or the system steers the vehicle (Minouï Enache, Netto, Mammari, & Lusetti, 2009). A main design concern is related to the quality of control transition, usually characterized by the *ease* for driver’s control resumption and the transition *smoothness* (Katzourakis, Lazic, Olsson, & Lidberg, 2015). Analyzed within the hierarchy of driving task proposed by Michon (1985), the driver’s steering override could be an *operational* effort in a sense of making micro-corrections of vehicle trajectories or avoiding a sudden hazard event in the vehicle pathway. At a higher level, the driver may sometimes intervene in steering control to fulfill *tactic* goals, e.g., a lane change to overtake a slow vehicle. In order to meet this potential need at the tactical level, we approach the design of driver steering override from a *cooperation* perspective. To this end, we aim at designing a cooperative steering control framework for AD systems that not only facilitates the driver to resume steering control whenever he desires but also assists the driver by detecting his intention. Given that the system does not simply suspend its control when the driver intervenes, we adopt a shared control approach to handle the control allocation.

This paper is divided in two parts. The first part presents the design of a shared control framework based on model predictive control (MPC) for driver steering override. The second part is dedicated to the evaluation of the designed framework. It presents a preliminary simulator experiment and discusses the experiment results.

2. MPC-based haptic shared control framework

Shared control inherits the control theory to determine the final control input for a plant when human and automation perform controls simultaneously (Abbinck & Mulder, 2010). Haptic shared control emphasizes that the driver and the system exert forces on the control interface such that the driver can continuously feel the activity of the system (Abbinck, Mulder, & Boer, 2012). A challenging issue of haptic shared steering control is the management of the conflict which arises when the driver tends to counter steer the system (de Winter & Dodou, 2011). Proposed solutions consist of formulating a fixed degree of control allocation as part of control objective (Saleh, Chevrel, Claveau, Lafay, & Mars, 2013; Mars, Deroo, & Hoc, 2014; Soualmi, Sentouh, Popieul, & Debernard, 2014) or modulate the steering torque of the controller online (Nguyen, Sentouh, & Popieul, 2017). Nevertheless, these cited solutions address the interference between the driver and the system only at the operational level, i.e., the system simply reduces its control once the conflict arises, without considering the potential difference between driver’s goal and system’s goal. In our framework, we extend a haptic shared control scheme to the tactical level by designing a function that detects the driver’s lane-change intention. Meanwhile at the operational level, we take advantage of the online optimization property of MPC to achieve a smooth control transition.

Fig. 1 shows the architecture of the proposed shared control framework. It is decomposed into two layers based on the hierarchy of the driving task of Michon. At the operational layer, a predictive shared steering control function assumes automatic steering control while sharing the control authority with the driver. At the tactical layer, an Active Lane Change Assist function can automatically perform a lane-change maneuver if the driver’s intention is detected from his actions on the steering wheel.

2.1. Predictive shared control

We formulate driver steering override as a haptic shared control problem implemented by MPC. MPC is a finite-horizon optimal control approach that iteratively minimizes a cost function defined for a plant model subject to state and input

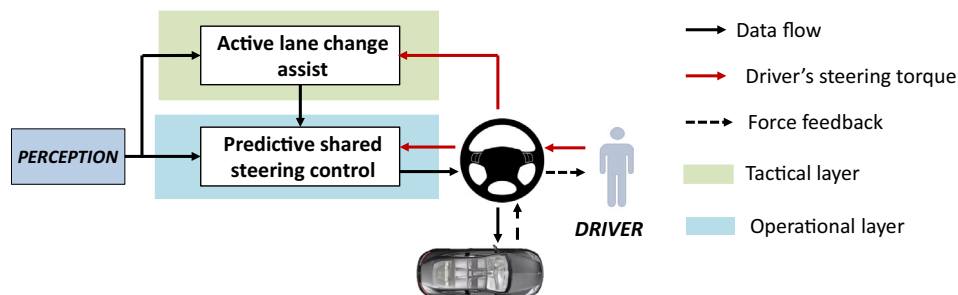


Fig. 1. Diagram of the MPC-based shared control framework.

constraints (Camacho & Bordons, 1999). The MPC controller bases its predictions on a linear bicycle vehicle model which is augmented with the steering system and the vehicle positioning dynamics for lane tracking. The control input for this model is the steering torque on the steering wheel. We refer the reader to (Soualmi et al., 2014) for the details of this model. A quadratic cost function over a prediction horizon of N sampling intervals is defined as

$$J_N = \rho J_{out} + J_{in}, \quad (1)$$

where J_N is the total cost, J_{out} is the cost penalizing the deviation of the controlled trajectory from a reference and J_{in} penalizing the system's control efforts. The variable ρ is referred to as *shared control policy* that leverages the control allocation. To make the driver have a good steering feel during the steering override, ρ is set to zero when the driver's steering intention is detected. In this way, the MPC controller shares the most control authority to the driver. When the driver releases the steering wheel, ρ becomes one. The MPC controller then resumes control to guarantee a seamless control transfer. The conditions for the binary variation of ρ are expressed by

$$\rho = 0, \quad \text{if } \gamma_{sw} > 0 \wedge |T_{dr}| > T_{thre} \wedge \gamma_{ma} = 0, \quad (2a)$$

$$\rho = 1, \quad \text{if } \gamma_{sw} = 0 \vee |\gamma_{ma}| = 1, \quad (2b)$$

where γ_{sw} is the output of a steering wheel hand position sensor, T_{dr} is the driver's steering torque, T_{thre} is a positive threshold to detect the driver's steering intention and γ_{ma} is the maneuver state of Active Lane Change Assist. To detect the driver's steering intention, we first employ a steering wheel hand position sensor to detect the driver's hand contact on the steering wheel. $\gamma_{sw} > 0$ means that at least one hand is detected whereas $\gamma_{sw} = 0$ means hands off. The driver may put his hands on the steering wheel while loosely following the rotation of the steering wheel. To avoid false alarm, a threshold T_{thre} is set on the driver's steering torque. We define T_{thre} as 1 Nm based on the recorded data in a preliminary simulator test. In order to hand over the control to the controller, the driver needs to release the steering wheel ($\gamma_{sw} = 0$). Another case in which the controller actively resumes the control authority is to assist the driver to perform a lane-change maneuver ($|\gamma_{ma}| = 1$). Lastly, ρ is followed by a first-order filter with time lag t_ρ to generate a smooth variation between zero and one.

Furthermore, we set the following constraints on the system's steering torque (control input):

$$|T_{ctrl}| \leq T_{max}, \quad (3a)$$

$$|\Delta T_{ctrl}| \leq \Delta T_{max}, \quad (3b)$$

where T_{max} is the maximum steering torque which is defined as 6 Nm so that the systems control can always be overridden by the driver, and ΔT_{max} is the maximum control increment to avoid the abrupt change of the system's control. Under the assumption of steady steering state, ΔT_{max} is proportional with the maximal increment of vehicle's lateral acceleration Δa_{y_max} (Mitschke & Wallentowitz, 2004)

$$\Delta T_{max} = K \Delta a_{y_max} = K j_{y_max} \Delta T, \quad (4)$$

where K is a constant depending on vehicle's parameters, j_{y_max} is the maximal lateral jerk and ΔT is the time sample size. For highway driving, j_{y_max} can be set as 0.9 m/s³ to ensure driver's comfort (AASHTO, 2010) and ΔT_{max} can be computed according to (4).

2.2. Active lane change assist

Many features can be used in the algorithm for driver's lane change intention detection, such as driver's behavior (steering wheel angle, head movement), vehicle state (speed acceleration, heading, yaw rate) and environment state (lateral and heading errors to a road, relative distances with other traffic vehicles). In order to estimate a relation between the unobservable driver's intention and some observable features, learn-based approaches are often used, e.g., training a support vector machine classifier (Mandalia & Salvucci, 2005; Kumar, Perrollaz, Lefèvre, & Laugier, 2013) or training a hidden Markov model (Berndt, Emmert, & Dietmayer, 2008; Kuge, Yamamura, Shimoyama, & Liu, 2000). Those learned-based approaches were demonstrated to be effective, however, to decide pertinent features and to prepare a representative dataset are not trivial.

We adapt the method proposed by Houenou, Bonnifait, Cherfaoui, and Yao (2013) to detect the driver's lane-change intention. The idea is to monitor the lateral and heading deviations of the position of the AD vehicle to the lane center. Since the MPC controller performs lane keeping without the driver's intervention, these deviations should be small. If these deviations to the lane center surpass a threshold and the driver is steering toward the direction to increase this deviation, then the driver's lane change intention detection is declared. The advantage of this method resides in the limited features used for the detection and its intuitiveness. At each instant k , the following quadratic error function is used to measure the deviation of the ego vehicle's center of gravity (CoG) to the lane center

$$D(k) = w_d \Delta d(k)^2 + w_\psi \Delta \psi(k)^2 \quad (5)$$

where Δd is the lateral offset of the ego vehicle's CoG to the lane center, $\Delta \psi$ is the heading error, and w_d and w_ψ are the weights. Driver's left lane-change intention is detected if

$$(\gamma_{ma} = 0) \wedge (D(k) > D_0) \wedge (D(k) > D(k-1)) \wedge (T_{dr} > T_{thre}), \quad (6)$$

where the condition $\gamma_{ma} = 0$ means the system's current maneuver state is lane-keeping. D_0 is a threshold whose value needs to be tuned experimentally. The condition $T_{dr} > T_{thre}$ implies that the driver intends to turn the steering wheel to the left. Symmetrically, it is only needed to change $T_{dr} > T_{thre}$ in (6) to $T_{dr} < T_{thre}$ for right lane change intention detection. Once the driver's left/right lane intention is detected, the maneuver state γ_{ma} is adapted to -1 and 1 respectively. The condition for the transition from a right lane maneuver to the lane-keeping maneuver is expressed as

$$((D(k) < D_0) \wedge (D(k) < D(k-1))) \vee (T_{dr} \cdot T_{ctrl} < -\lambda), \quad (7)$$

where $T_{dr} \cdot T_{ctrl}$ is an indicator of the negative interference between the driver and the system which was originally proposed by [Sentouh, Soualmi, Popieul, and Debernard \(2013\)](#), and λ is a positive threshold which is set as $3.5 \text{ N}^2 \text{ m}^2$.

We tuned the parameters in the above described algorithm based on a dataset collected from our previous driving simulator experiments on highway driving. There were totally 36 lane change maneuvers in this dataset. The retained parameters are showed in [Table 1](#).

During the parameter tuning, the focus was laid on the threshold D_0 . We proposed three metrics to evaluate the performance of the algorithm—detection rate, false alarm rate and prediction time. The definitions of these metrics are illustrated in [Fig. 2](#). The performance metrics with different threshold values are listed in [Table 2](#) in which the selected value is enclosed.

3. Experimental protocol

This section describes a preliminary user study with the purpose to investigate the following aspects of the shared control based override mode:

- The ease for the driver to regain control from the system and the smoothness of control transition;
- How users interact with the Active Lane Change Assist and its effect on user's performance.

Table 1
Tuned parameters for driver's lane change intention detection.

Symbol	Description	Value [units]
w_d	Weight on lateral deviation	1
w_ψ	Weight on heading (yaw) angle deviation	3000
D_0	Threshold on the divergence metric	3

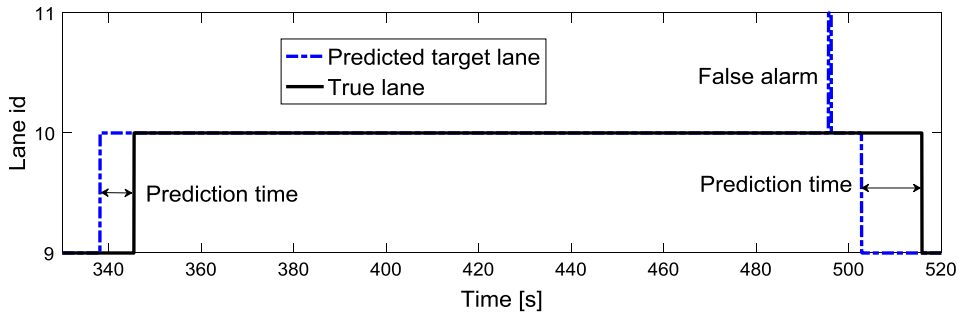


Fig. 2. Illustration of the proposed performance metrics.

Table 2
Detection performance metrics under different threshold values.

Threshold value	Detection rate	False alarm rate	Average prediction time
1	100%	35.3%	2.7 s
2	100%	10.5%	2.15 s
3	100%	2.63%	1.65 s
4	100%	2.63%	1.45 s
5	89.2%	5.71%	1.2 s
6	78.3%	0%	1.05 s

3.1. Configurations

In this study, we compared four configurations which represented four different steering interaction forms. They are listed in Table 3. By setting the configuration SHC, we created a comparison group to SHC_ALCA in order to assess the effect of the ALCA during lane change maneuvers. FUA represents a type of automatic steering controller that does not share the control with the driver. In this configuration, the driver needs to override it with a large steering torque (5 Nm in our study). Finally, HAS represents another extremity in terms of control sharing, since a small amount of the driver's steering action can lead to the deactivation of the system.

3.2. Participants

Twelve participants, average age of 34.0 years (ranging from 24 to 61) took part in the experiment. They came from the University of Valenciennes with three different backgrounds: student, engineer and professor. They had between 1 and 37 years of driving experience (mean 13.5 years \pm 13.3).

3.3. Apparatus, system and interface

A fixed-base driving simulator of LAMIH laboratory was used in this user study. A LCD was used for the visual display. The driving simulation was powered by SCANer Studio (OKTAL, 2015). A SENSODRIVE electric motor (SENSODRIVE, n.d.) rendered the torque generated by the shared steering controller. The driver's steering torque was estimated from the current in the DC motor of the SENSO-Wheel by its control unit.

The whole AD system integrated in the driving simulator comprised a mode transition module, a vehicle longitudinal controller developed in our previous work (Guo, Sentouh, Popieul, Soualmi, & Haué, 2015) and the shared steering controller developed in this paper. The mode transition module allows subjects to switch between a manual driving mode and an AD mode by a "mode button". The AD system disengages the steering control if the absolute value of the driver's steering torque exceeds a predefined threshold which was set to 1 Nm for HAS and 5 Nm for the other three configurations. Once the steering control is disengaged, the AD system enters a "Longi control" mode where the system performs only vehicle longitudinal control. To reengage the automatic steering control from this mode, subjects need to press a "steering control button".

HMI graphics were directly overlaid in the virtual driving scene, as shown in Fig. 3. In the top-right corner of the screen, the current driving mode was shown. In the top-middle zone, a blue arrow was displayed to represent the maneuver state of the Active Lane Change Assist. In the configuration SHC_ALCA, if a participant initiated a lane-change, this arrow changed its direction to signify the acknowledgement.

Table 3
Four steering interaction configurations tested in the user study.

Name	Acronym	Description
Shared control with Active Lane Change Assist	SHC_ALCA	It refers to the whole framework illustrated by Fig. 1. This configuration features both the "predictive shared steering control" and "ALCA" functions
Shared control	SHC	This configuration has only the "predictive shared steering control" function compared to SHC_ALCA. To perform LC, the driver needs to drive manually into the target lane, then the AD vehicle stays in the new lane
Full autonomy	FUA	This configuration fixes the shared control policy at one. In this way, the predictive shared steering control resumes the full steering authority. It opposed to any driver's control that could cause a deviation to its reference
Haptic switch	HAS	Whenever the driver's steering intention is detected, the predictive shared steering control is disengaged. The driver regains the full steering authority immediately. The driver needs to reactivate the controller before releasing the steering wheel

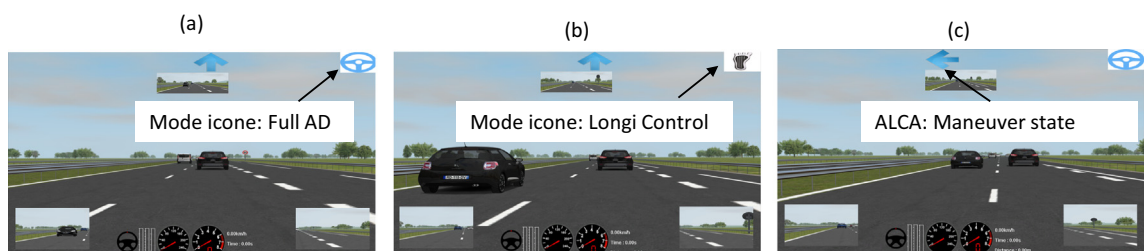


Fig. 3. Visual HMI used in the user test: (a) mode icon for the Full AD mode; (b) mode icon for the Longi Control mode; (c) icon for the later maneuver state.

3.4. Test scenarios

The test course in the simulator was composed by a ramp track and a highway mainline track. Each test run was made up of two scenarios. As shown in Fig. 4, the starting position of the ego vehicle was located on the ramp track. The ego vehicle first entered in Scenario A—passing a roadwork zone. In this scenario, subjects needed to adjust the vehicle's trajectory towards the left side to keep a safe distance with the road barriers. After this scenario, the ego vehicle merged in a two-lane highway mainline. The road limit was 90 km/h, but the traffic vehicles in the right lane were made purposely drive at 70 km/h to justify our instruction on overtaking. The gaps between traffic vehicles on the left lane were large enough to ensure that each subject could perform lane-change with ease.

3.5. Test procedure and instructions

A within-subject design was employed in this study, i.e., each participant tested all the four configurations. We randomized the order of test configurations to minimize the order effect. Prior to the test drive, the subjects got accustomed to the AD system and the driving simulator in a training course without any traffic. In this phase, we explained possible deactivations of the automatic steering control in different configurations. After this training phase, each subject was instructed to drive the test course manually to get familiar with the scenarios. In the meanwhile, each subject was told what they should do in the test runs.

Before the test runs, we gave a general instruction—use the automatic steering control as long as possible for all the configurations. This instruction accounted for deactivations of the automatic steering controller which could occur frequently in HAS. If a subject did not reactivate the controller, he would remain in manual steering control that could bias the test results. Moreover, subjects were asked to put their hands off the steering wheel when they did not perform required control tasks. Before the test run of the SHC_ALCA configuration, we described the mechanism of the Active Lane Change Assist and the meaning of the blue arrow in the screen. The main test procedure summarized in Fig. 5.

3.6. Metrics

We selected two objective metrics to measure driver's steering performance during the control transition. The first metric was the root-mean-square of the driver's steering torque, $RMS(T_{dir})$ which was defined by

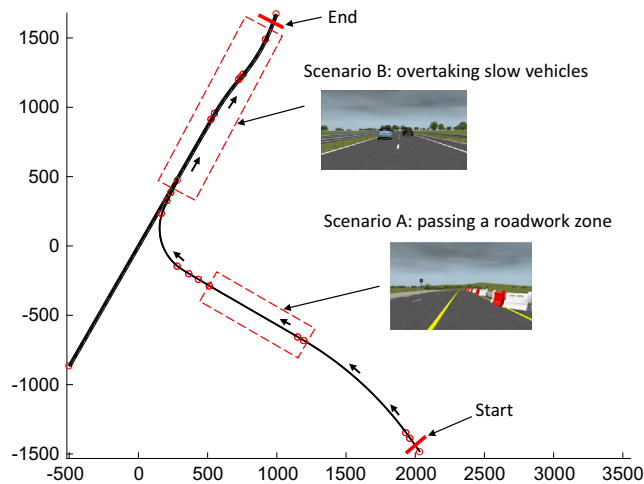


Fig. 4. Test course and scenarios.

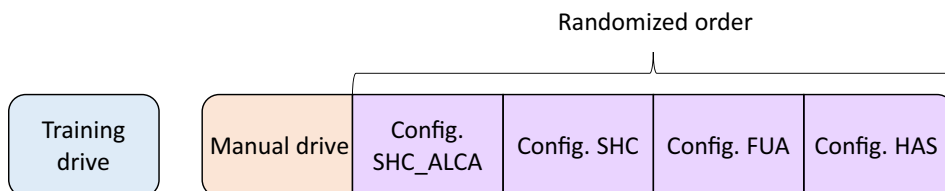


Fig. 5. Test procedure.

$$RMS(T_{dr}) = \sqrt{\frac{\int_{t_0}^{t_1} T_{dr}^2 dt}{t_1 - t_0}}, \quad (8)$$

where t_0 and t_1 are the start time and the end time of a range of interest in the collected data. For the Scenario A (roadwork zone), the range of interest started from the instant when a subject began to turn the steering wheel (detected by the sensor on the steering wheel) until the adjusted lateral trajectory was stabilized. For the scenario B (highway overtaking), the range of interest was defined as the time window of a LC maneuver. We used the method for driver's lane-change intention detection to determine the range of a lane-change maneuver. $RMS(T_{dr})$ measures the steering effort of a subject in the presence of a steering controller.

As the second objective metric, we measured the number of steering wheel reversals (SWR) in a range of interest. According to the definition given by the standard SAE (2015), a SWR occurs when a steering wheel rotates at least Δa deg in one direction and then rotates at least Δa deg in the opposite direction within a moving time window Δt . We used the method proposed by the AIDE project (Östlund et al., 2005) to count SWRs with Δa equals to 3 deg. The same ranges of interest used to calculate $RMS(T_{dr})$ were applied here for Scenario A and B as well. SWR represents large steering corrections, therefore, more SWRs means that the control transition is less smooth.

Subjective evaluation was based on questionnaires. After each configuration, subjects were asked to answer a questionnaire related to their experiences with this configuration. In this questionnaire, they were asked to rate their *efficiency*, *feeling of comfort*, *perceived safety*, and *ease of trajectory control* when they took over the control from the system. Each item had a four-point scale.

4. Results

4.1. Results of typical runs

This section shows how a subject interacted with the steering controller in different configurations in some typical runs. Figs. 6 and 7 show the results for the trajectory adjustment in Scenario A by a same subject through SHC and HAS respectively. In Fig. 6, the predictive shared steering controller smoothly reduced its control to give the full authority to the driver following the condition (2a). As a result, the resultant steering wheel angle remained between -2 deg and 2 deg. Thanks to the hand position sensor, the controller was aware that the driver held the steering wheel during the override and thus did not resume the control even if the driver's steering torque was small. This mechanism prevents the intrusion of the controller when the driver exerts only slight control, e.g., when a driver maintains an offset to a lane center in a straight road. In contrast, abrupt deactivations of the controller (system's mode from "1" to "0") in HAS caused SWRs of the steering wheel (exceeding 5 deg in the first SWR and 10 deg in the second, as shown in Fig. 7). What's more, whenever the driver intervened to correct the vehicle's trajectory, he deactivated the controller and he needed to reengage the controller to benefit the automatic control.

Fig. 8 illustrates a lane-change maneuver performed by a subject with the configuration SHC_ALCA. When the right lane-change intention of the subject was detected by Active Lane Change Assist (see the plot "maneuver state"), the controller resumed the control authority (see the plot "shared control policy"), and performed the lane-change in the place of the subject. Within the designed haptic shared control framework, the subject could feel the system's activity directly by the force

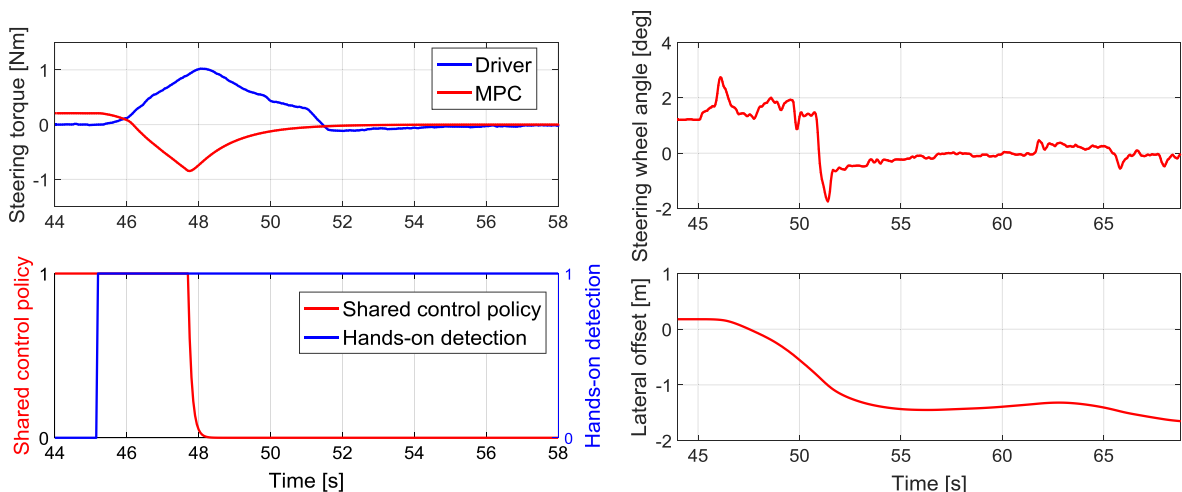


Fig. 6. Plot of a typical run of configuration SHC in Scenario A.

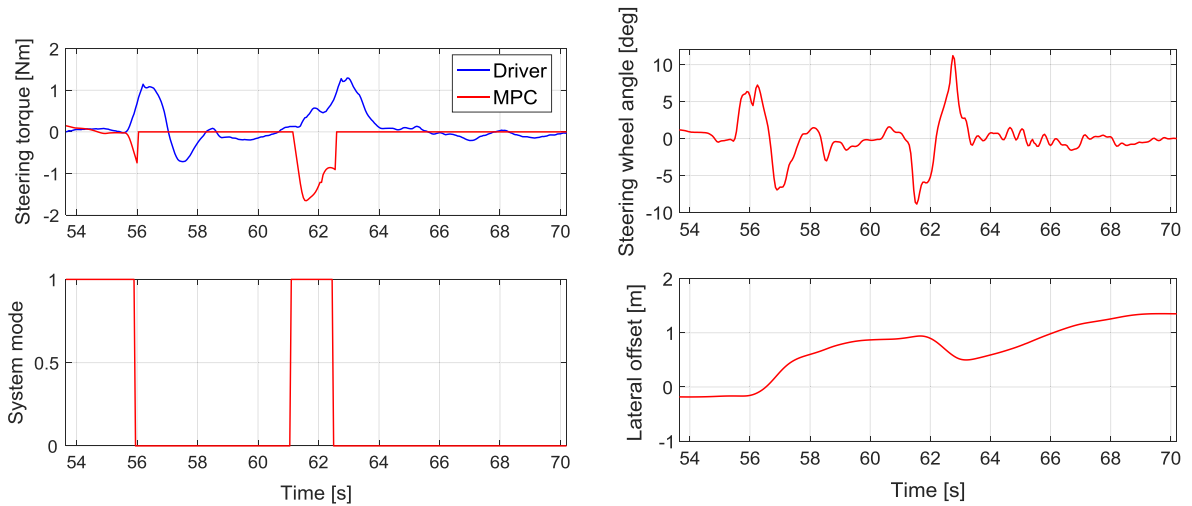


Fig. 7. Plot of a typical run of configuration HAS in Scenario A.

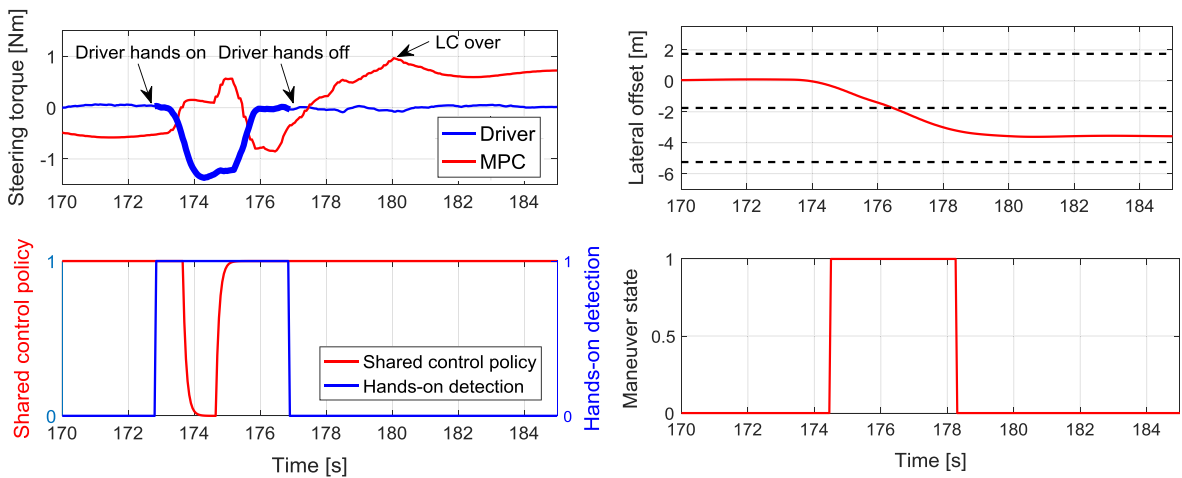


Fig. 8. Plot of a typical run of configuration SHC_ALCA in Scenario B.

feedback. Consequently, the subject first reduced his control then released the steering wheel about 3 s before the vehicle reached the target lane center.

4.2. Statistical results

One-way analysis of variance (ANOVA) was used for statistical analysis with a significance level of 0.05. Turkey HSD tests were used for post hoc analysis.

Fig. 9 shows the results of $RMS(T_{dr})$ in Scenario A and B. There were statistically significant differences in $RMS(T_{dr})$ among the four configurations in both Scenario A ($F(3, 44) = 131.77, p < .0001$) and Scenario B ($F(3, 61) = 48.22, p < .0001$). As expected, post hoc Turkey HSD tests showed that the driver's steering effort was significantly reduced in SHC_ALCA, SHC and HAS compared to FUA in both scenarios ($p < .01$). For example, in SHC subjects saved on average 85.2% effort in Scenario A and 62.9% effort in Scenario B compared to FUA. However, the post hoc analysis revealed that there were no significant differences in the $RMS(T_{dr})$ in Scenario B between SHC_ALCA and SHC. This observation indicates that the ALCA did not reduce the driver's steering effort in lane changes, though it was intended to support the driver to perform lane change maneuver.

Statistical results of SWR are presented in Fig. 10. The ANOVA revealed significant effects of the configurations in Scenario A ($F(3, 42) = 3.9, p < .015$). Especially, HAS had the highest average number of SWRs, i.e., the driver made more steering corrections to adjust the vehicle's trajectory when interacting with the steering controller than in the other three configurations. Compared to HAS, SHC significantly reduced the SWRs by 70% ($p < .05$), thus leading to a smoother control transition.

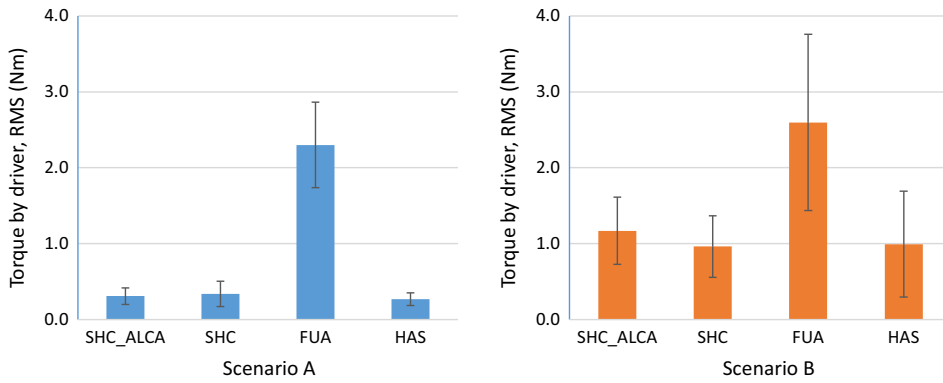


Fig. 9. RMS of driver's steering torque in the different configurations in Scenario A and B.

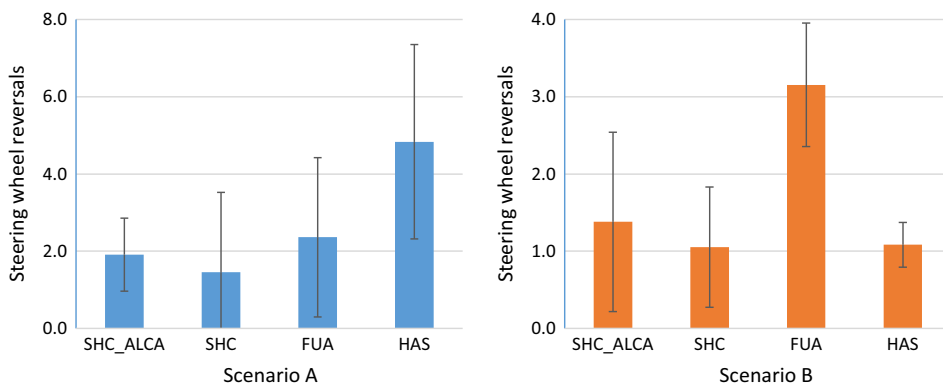


Fig. 10. Steering wheel reversals in the different configurations in Scenario A and B.

In Scenario B, there was also a significant difference on the steering wheel reversals ($F(3, 61) = 18.05, p < .0001$). FUA yielded the highest steering reversals in Scenario B. It was mainly due to much stronger resistances a subject received from the steering controller during a lane change. Some subjects even triggered the deactivation of the steering controller by exceeding the maximum torque threshold. In contrast, deactivations in HAS did not have significant effects on the SWR (with no significant difference compared to SHC) during lane changes. The SWR in SHC_ALCA had wide variance between subjects ($SD = 1.16$). It means that some subjects attempted to correct controller's actions rather than follow them.

Fig. 11 shows the mean values of the responses on each item in the questionnaire (standard deviations on each item are omitted for figure clarity). There were significant effects of the configurations in comfort ($F(3, 44) = 6.33, p < .001$) and sense of control ($F(3, 44) = 6.33, p < .0006$). There were no significant differences between the four configurations in efficiency of regaining control and safety feeling. Except for the item efficiency, SHC received the highest rating in terms of comfort ($M = 3.42, SD = 0.67$), safety ($M = 3.42, SD = 0.67$) and control ($M = 3.75, SD = 0.45$).

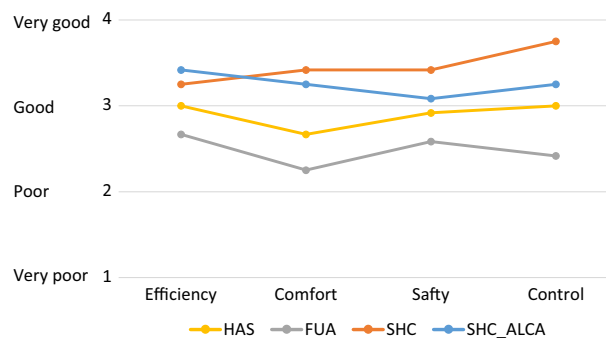


Fig. 11. Subjective evaluation of the four configurations in terms of efficiency, comfort, safety and control feeling.

5. Discussion

Statistical analysis based on objective metrics suggest that with the predictive shared steering controller (SHC) users used much less steering efforts to adjust vehicle's lateral trajectory than with an automatic steering controller that did not adapt control to that of the driver (FUA). When the driver took over control to adjust lane positions in Scenario A, the predictive shared steering controller ensured a smoother control transition than a controller that can be deactivated by a small steering torque of the driver (HAS). These two conclusions are also confirmed by subjective ratings, as SHC received two highest ratings in terms of sense of control and comfort.

Concerning Active Lane Change Assist, some subjects benefited from the support of the MPC controller during lane changes, as demonstrated by a typical run shown in Fig. 8. However, the average steering effort of subjects to perform lane change was not reduced with Active Lane Change Assist. Meanwhile, the SWR number had large variance between subjects. A driving simulator study by Fricke, Griesche, Schieben, Hesse, and Baumann (2015) reported that a majority of subjects tended to hold the steering wheel strongly or counter-steer during the first encounter with an automatic steering intervention. In the current design, the MPC controller first minimizes its control when the driver begins to steer. It exerts control again on the detection of driver's lane-change intention. Even though the controller's torque is in the same direction with that of driver, this injected torque could be felt as an intrusion by some of subjects, particularly considering that the subjects were not familiarized with Active Lane Change Assist before test runs. Furthermore, according to our interviews, some subjects reported that they did not have confidence on the automation as new users. This remark was also confirmed by the relatively low ratings for SHC_ALCA in terms of safety and control feel compared with SHC, as illustrated in Fig. 11. Another plausible cause may be related to the interference on lane-change trajectory between subjects and the controller. The trajectories realized by the MPC controller are influenced by the weights in the cost function. Subjects with different driving styles may have different accustomed trajectories for lane changes. The deviation between the subject's expected trajectory and that of the steering controller could incite subject's steering corrections, thus increasing SWRs.

6. Conclusions

This paper has presented a shared steering control framework that allows a driver to override an AD system's steering control. This framework consists of two layers. At the operational layer, a haptic shared steering controller was implemented in the MPC framework. By adapting the weight in the cost function and implementing control input constraints, the shared steering controller ensures a seamless and smooth control transfer between the system and the driver. The function at the tactical layer, namely Active Lane Change Assist, detects the driver's lane-change intention and assists the driver during a lane change. The designed framework was evaluated in a preliminary simulator study in comparison with other three steering interaction concepts. The test results show that the designed framework allowed subjects to override system's control easily and smoothly. We also note that subject steering efforts were not reduced with system's assistance during lane change maneuvers. The hypotheses on the causes are discussed lastly.

In the current framework, the shared control policy varies in a binary fashion, which could make system's assistance felt as an intrusion by users. It would be of interest to study different variation forms that can result in smoother system behaviors in future research. Furthermore, the decision on control allocation may take into account more factors in addition to driver's steering intention and maneuver intention. Particularly, how to handle a careless override from the driver needs to be addressed. With regards to human factors evaluation, a user study could be conducted in the future to verify whether the user's performance in using Active Lane Change Assist will increase as they get used to the system.

Acknowledgements

This work is part of the project "Localization & Augmented Reality", which is supported by the French government as part of PIA (French acronym for Program of Future Investments) within the Technological Research Institute SystemX.

References

- AASHTO (2010). *A policy on geometric design of highways and streets, 6th Edition* (6th Edition). American Association of State Highway and Transportation Officials. Retrieved from <https://bookstore.transportation.org/collection_detail.aspx?ID=110>.
- Abbink, D. A., & Mulder, M. (2010). Neuromuscular Analysis as a Guideline in designing Shared Control. In M. Hosseini (Ed.), *Advances in Haptics*. InTech. Retrieved from <<http://www.intechopen.com/books/howtoreference/advances-in-haptics/neuromuscular-analysis-as-a-guideline-in-designing-shared-control>>.
- Abbink, D. A., Mulder, M., & Boer, E. R. (2012). Haptic shared control: Smoothly shifting control authority? *Cognition, Technology & Work*, 14(1), 19–28. <https://doi.org/10.1007/s10111-011-0192-5>.
- Aeberhard, M., Rauch, S., Bahram, M., Tanzmeister, G., Thomas, J., Pilat, Y., ... Kaempchen, N. (2015). Experience, results and lessons learned from automated driving on Germany's highways. *IEEE Intelligent Transportation Systems Magazine*, 7(1), 42–57. <https://doi.org/10.1109/ITS.2014.2360306>.
- Berndt, H., Emmert, J., & Dietmayer, K. (2008). Continuous driver intention recognition with hidden Markov models. In *2008 11th International IEEE conference on intelligent transportation systems* (pp. 1189–1194). <http://doi.org/10.1109/ITSC.2008.4732630>.
- Blanco, M., Atwood, J., Vasquez, H., Trimble, T., Fitchett, V., Radlbeck, J., ... & Sheldon, R. (2015). *Human factors evaluation of Level 2 and Level 3 automated driving concepts* (No. DOT HS 812 182) (p. 320). Retrieved from <<https://trid.trb.org/view/1357796>>.
- Camacho, E. F., & Bordons, C. (1999). *Model predictive control*. Retrieved from <<http://cds.cern.ch/record/601666>>.

- de Winter, J. C. F., & Dodou, D. (2011). Preparing drivers for dangerous situations: A critical reflection on continuous shared control. In *2011 IEEE International conference on Systems, Man, and Cybernetics (SMC)* (pp. 1050–1056). <http://doi.org/10.1109/ICSMC.2011.6083813>.
- Endsley, M. R., & Kiris, E. O. (1995). The out-of-the-loop performance problem and level of control in automation. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *37*(2), 381–394. <https://doi.org/10.1518/001872095779064555>.
- Fricke, N., Griesche, S., Schieben, A., Hesse, T., & Baumann, M. (2015). Driver behavior following an automatic steering intervention. *Accident Analysis & Prevention*, *83*, 190–196. <https://doi.org/10.1016/j.aap.2015.07.018>.
- Guo, C., Sentouh, C., Popieul, J.-C., Soualmi, B., & Haué, J.-B. (2015). Shared control framework applied for vehicle longitudinal control in highway merging scenarios. In *2015 IEEE international conference on Systems, Man, and Cybernetics (SMC)* (pp. 3098–3103). <http://doi.org/10.1109/SMC.2015.538>.
- Houenou, A., Bonnifait, P., Cherfaoui, V., & Yao, W. (2013). Vehicle trajectory prediction based on motion model and maneuver recognition. In *2013 IEEE/RSJ international conference on Intelligent Robots and Systems (IROS)* (pp. 4363–4369). <http://doi.org/10.1109/IROS.2013.6696982>.
- Katzourakis, D. I., Lasic, N., Olsson, C., & Lidberg, M. R. (2015). Driver steering override for lane-keeping aid using computer-aided engineering. *IEEE/ASME Transactions on Mechatronics*, *20*(4), 1543–1552. <https://doi.org/10.1109/TMECH.2015.2401044>.
- Kuge, N., Yamamura, T., Shimoyama, O., & Liu, A. (2000). A driver behavior recognition method based on a driver model framework. *SAE Technical Paper 2000-01-0349*. <http://doi.org/10.4271/2000-01-0349>.
- Kumar, P., Perrollaz, M., Lefèvre, S., & Laugier, C. (2013). Learning-based approach for online lane change intention prediction. In *2013 IEEE intelligent vehicles symposium (IV)* (pp. 797–802). <http://doi.org/10.1109/IVS.2013.6629564>.
- Mandalia, H. M., & Salvucci, M. D. D. (2005). Using support vector machines for lane-change detection. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *49*(22), 1965–1969. <https://doi.org/10.1177/154193120504902217>.
- Mars, F., Deroo, M., & Hoc, J. M. (2014). Analysis of human-machine cooperation when driving with different degrees of haptic shared control. *IEEE Transactions on Haptics*, *7*(3), 324–333. <https://doi.org/10.1109/TOH.2013.2295095>.
- Michon, J. A. (1985). A critical view of driver behavior models: What do we know, what should we do? In L. Evans & R. C. Schwing (Eds.), *Human Behavior and Traffic Safety* (pp. 485–524). Springer US. Retrieved from http://link.springer.com/chapter/10.1007/978-1-4613-2173-6_19.
- Minoui Enache, N., Netto, M., Mammari, S., & Lusetti, B. (2009). Driver steering assistance for lane departure avoidance. *Control Engineering Practice*, *17*(6), 642–651. <https://doi.org/10.1016/j.conengprac.2008.10.012>.
- Mitschke, M., & Wallentowitz, H. (2004). *Dynamik der Kraftfahrzeuge* (4. neu bearb. Aufl. 2004). Berlin: Springer.
- Nguyen, A. T., Sentouh, C., & Popieul, J. C. (2017). Driver-automation cooperative approach for shared steering control under multiple system constraints: Design and experiments. *IEEE Transactions on Industrial Electronics*, *64*(5), 3819–3830. <https://doi.org/10.1109/TIE.2016.2645146>.
- OKTAL. (2015). *SCANeR Studio user manual-simulation mode*. OKTAL SAS.
- Östlund, J., Peters, B., Thorslund, B., Engström, J., Markkula, G., Keinath, A., . . . & Foehl, U. (2005). *Driving performance assessment – methods and metrics* (No. Project IST-1-507674-IP, Deliverable 2.2.5). EU project AIDE. Retrieved from http://www.aide-eu.org/res_sp2.html.
- PREVENT. (2009). *Code of Practice for the Design and Evaluation of ADAS* | ACEA - European Automobile Manufacturers' Association (No. PREVENT Report 11300). Retrieved from https://www.acea.be/uploads/publications/20090831_Code_of_Practice_ADAS.pdf.
- SAE (2015). *Operational definitions of driving performance measures and statistics* (Standard No. J2944_201506) (p. 171). SAE International.
- SAE (2016). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (Standard No. J3016_201609) (p. 30). SAE International.
- Saleh, L., Chevrel, P., Claveau, F., Lafay, J. F., & Mars, F. (2013). Shared steering control between a driver and an automation: Stability in the presence of driver behavior uncertainty. *IEEE Transactions on Intelligent Transportation Systems*, *14*(2), 974–983. <https://doi.org/10.1109/ITITS.2013.2248363>.
- SENSODRIVE. (n.d.). *Senso-Wheel SD-LC – the perfect one*. Retrieved February 14, 2017, from <https://www.sensodrive.de/EN/products/Force-Feedback-Wheels/Senso-Wheel-SD-LC.php>.
- Sentouh, C., Soualmi, B., Popieul, J. C., & Debernard, S. (2013). Cooperative steering assist control system. In *2013 IEEE international conference on systems, Man, and Cybernetics* (pp. 941–946). doi: 10.1109/SMC.2013.165.
- Seppelt, B. D., & Victor, T. W. (2016). Potential solutions to human factors challenges in road vehicle automation. In *Road Vehicle Automation 3* (pp. 131–148). Springer, Cham. http://doi.org/10.1007/978-3-319-40503-2_11.
- Soualmi, B., Sentouh, C., Popieul, J. C., & Debernard, S. (2014). Automation-driver cooperative driving in presence of undetected obstacles. *Control Engineering Practice*, *24*, 106–119. <https://doi.org/10.1016/j.conengprac.2013.11.015>.
- Strand, N., Nilsson, J., Karlsson, I. C. M., & Nilsson, L. (2014). Semi-automated versus highly automated driving in critical situations caused by automation failures. *Transportation Research Part F: Traffic Psychology and Behaviour*, *27*, 218–228. <https://doi.org/10.1016/j.trf.2014.04.005>.
- UNECE (2016). *UNECE paves the way for automated driving by updating UN international convention*. Retrieved August 10, 2017, from <https://www.unece.org/info/media/presscurrent-press-h/transport/2016/unece-paves-the-way-for-automated-driving-by-updating-un-international-convention/doc.html>.
- Walch, M., Lange, K., Baumann, M., & Weber, M. (2015). Autonomous driving: Investigating the feasibility of car-driver handover assistance. In *Proceedings of the 7th international conference on automotive user interfaces and interactive vehicular applications* (pp. 11–18). New York, NY, USA: ACM. <http://doi.org/10.1145/2799250.2799268>.
- Wolf, I. (2016). The interaction between humans and autonomous agents. In *Autonomous driving* (pp. 103–124). Springer, Berlin, Heidelberg. http://doi.org/10.1007/978-3-662-48847-8_6.