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Online adaptation of the Level Of Haptic Authority in a lane keeping system considering the driver's state

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Abstract

Driver distraction is an important factor of accidents. Not only in manual driving, the driver state information is also interesting to consider in automated driving systems in order to provide the driver with a suitable assistance level in respect to his evolving needs. The concepts of adaptive automation and human machine cooperation suggest that the authority of the automation should be adapted in real time according to the situation. However, contrary to existing studies that demonstrated the benefits for continuous fixed haptic feedback in the lane keeping task, evidence regarding the potential benefits of online adaptation of the level of haptic feedback is still lacking. In this framework a study is conducted in order to investigate the effects of online adjusting the authority level of a lane keeping assist system to match the driver's distraction state while engaging in a demanding secondary task. The study took place in the SHERPA-lamih driving simulator. A comparison has been made between manual driving as a baseline, a Lane keeping Assist (LKA) providing a fixed and continuous haptic feedback and an Adaptive Lane Keeping Assist (ALKA). The analysis accounted for the driving performance and effort along with the subjective ratings of comfort, safety, control and workload. The results were consistent with the previous studies that showed the benefits of fixed haptic feedback under normal driving conditions. Moreover, the study established the benefits of adapting the level of haptic authority when the drivers were engaged in a secondary task. Furthermore, some design issues are highlighted for the design of effective adaptive automation.

Keywords: Human-machine cooperation; Adaptive automation; Adaptive Lane Keeping Systems; Shared control; Driver distraction.

1. Introduction

With the increase of the road fleet during the last decades, many challenges have arisen regarding the safety of the roads and the underlying economic issues. Accompanying the great advances in sensing technologies and artificial intelligence has come the promise that the automation of the driving task would lead to the suppression of human error which is a major cause for car crashes (NHTSA 2008). In addition, many profits are to be achieved like time and energy saving by managing the traffic flow, decreasing congestion and increasing fuel efficiency (Litman 2014).

For these reasons, automated driving has been widely addressed in many research projects exploring the necessary technologies to safely operate automated vehicles (Aeberhard et al. 2015; Bauer et al. 2012; Hoeger et al. 2008; Sentouh et al. 2014). Although the ultimate goal is to achieve fully autonomous driving, many challenges remain unsolved and this technology still needs time to mature. In the meantime, organizations like the NHTSA (National Highway Traffic Safety Administration) and the OICA (International organization of motor vehicle manufacturers) have proposed taxonomies for addressing intermediate levels of automation (Blanco et al. 2015). The levels currently being tackled consider a conditional automation where the system fully (level 2 on the NHTSA scale) or partially (level 1) controls the vehicle while the driver remains responsible for the driving task. Therefore, the driver has seen his role shifted from control to supervision.

Among the lessons learnt throughout the various projects was the necessity to consider interactions with the driver and address the issues related to task allocation, authority management and automation levels during the system design process (Inagaki 2010; Bauer et al. 2012; Sentouh et al. 2014). It has been brought to our attention

by many studies in the literature that human factor issues due to a poorly designed automation can be critical to the driver's safety (Bainbridge 1983; Saffarian et al. 2012). Along with the loss of situation awareness (Kaber & Endsley 2004), common issues such as complacency and overreliance (Inagaki et al. 1999), trust (Dzindolet et al. 2003; Lee & See, 2004) and skill degradation (Young et al. 2007) can be encountered. In fact, a key element at these levels of automation is the design of an appropriate interaction between the driver and the system as the acceptance of the developed system fully depends on it. In this context, research on human-machine cooperation aim to lay down guidelines for designing effective human machine systems (Hoc & Lemoine 1998; Flemisch et al. 2014).

Today, many active systems already exist in real cars. They act on the vehicle's dynamics like the ESP or on longitudinal control like the adaptive cruise control (ACC). In this paper, a special attention is given to lateral control systems. It has been shown in (Carsten et al. 2012) that it is not only the increase of the level of automation that affects negatively the driver's attention but the automation support type also. In fact, the delegation of lateral control to an automatic steering system results in a lower driver engagement compared to longitudinal control delegation. Therefore, an understanding of the drivers' behaviour with lateral control systems is crucial for a proper design of the interactions with the system. One aspect that has been studied is the resumption of control after an automated phase. Control resumption might be needed when the system is unable to manage a particular driving situation or if the driver prefers to take over the control. (Merat et al 2014) investigated the time needed to take over control under distraction and found that drivers required around 35 et 40 seconds to stabilize the lateral control. Another study highlighted the impact of traffic density on take over times and quality and showed a negative influence of traffic density on the take-over performance (Gold et al. 2016). The control resumption was also assessed in the case where it was necessary to manually avoid an obstacle undetected by the automatic steering system (Hoc et al. 2006; Navarro et al. 2016). Hoc et al. (2006) highlighted the difficulty of returning to manual control when required. This result was confirmed in a similar study in (Navarro et al. 2016) which also revealed a change in the gaze behavior during the delegation of the lateral control.

As an alternative to lateral control delegation which puts the driver in a supervisory position, haptic shared control was investigated as an intuitive human-machine interface that meets the commonly voiced design guidelines, especially for automotive applications (Abbink & Mulder 2009; Abbink et al. 2012; Mulder et al. 2012; Mars et al. 2014). While keeping the human in the direct manual control loop, it offers a continuous interaction as the system actions are continuously felt and the driver is free to over-rule them in case of system error. Studies showed that it yields faster and more accurate vehicle control, lowers the required control effort and reduces demand for visual attention (Abbink et al. 2012). Haptic shared control is described as a continuous spectrum lying between manual control and full automation, and the Level of Haptic Authority (LoHA) defines the sharing of control authority between the system and the driver (Mulder et al. 2012). Considering a fixed LoHA, some existing studies faced the question of finding the best LoHA (Abbink & Mulder 2009; Mulder et al. 2012; Mars et al. 2014). Mars et al. (2014) found that the LoHA that provides the best compromise between the steering performance and the subjective feelings of comfort and safety was somewhere between both ends of the haptic shared control spectrum. They also showed that the optimal LoHA may vary according to visibility conditions. However, fixing the LoHA is in accordance with the human centered design approach that has long been used for automation design. It regards the human as the only responsible for the choice of the operating mode of the system. The fact that the human should always have the authority over the system was justified by him being ultimately responsible for the behavior of the latter. Furthermore, humans may be more efficient at managing resources when they can control changes in the state of automation (Billings & Woods, 1994). However, humans may fail to take proper actions in cases where their understanding of the situation is somewhat incorrect or incomplete or in cases where the time is critical to implement a necessary action (Inagaki 2008). Thereby, an alternative paradigm has been proposed to consider the possibility that the level of automation and operating mode might be modified in real time either by the human or the system. This approach is called adaptive automation (Scerbo 1996; Parasuraman et al. 1992; Inagaki 2003). Systems implementing the concept of adaptive automation have been introduced and studied since the nineties (Parasuraman et al. 1996). The idea

of accounting for psychophysiological indices that reflect the underlying cognitive activity and arousal levels was interesting to explore. In (Pope et al. 1995; Freeman et al. 1999), EEG signals have been used to characterize the operator engagement index which was used to switch between manual and automatic modes in a supervision and tracking task application. These studies have shown that the system could moderate the workload. Adaptive automation has also proven to increase performance as reported in an experiment (Wilson & Russell 2004) where in addition of the EEG, multiple signals (heart, blink, and respiration rates) have been used to trigger the changes in automation. However a major technical issue for using physiological signals lies in the intrusiveness of the measurement methods which cannot be envisaged in the automotive domain. Alternatively, solutions for driver monitoring with camera based detection of the driver distraction and fatigue states already exist.

The concept of adaptive automation combined with haptic shared control leaves us with the possibility of traveling continuously along the whole spectrum of haptic shared control. Some works have been investigating the design of effective approaches to dynamically manage the authority between the driver and the assistance system (Sentouh et al. 2013; Soualmi et al. 2014; Nguyen et al. 2015). The goal here is to allow real-time adaptive and continuous sharing of control depending on the driving situation and the driver's state and intent. However, evidence regarding the benefits and acceptability of this kind of systems are lacking and some authors show reluctance to the idea (Mars et al. 2014).

This background motivated the conduction of an experiment to assess the impacts of the online adaptation of the level of haptic assistance according to the driver's state. The aim is to give some insight regarding the use of driver distraction and fatigue information delivered by an off the shelf driver monitoring system in order to online modulate the authority level of a haptic shared control system. The latter provides continuous haptic feedback on the steering wheel for lane keeping assistance. Due to the adaptive nature of the system we refer to it as Adaptive Lane Keeping Assist (**ALKA**).

A comparison has therefore been made with manual driving as a baseline and with a haptic shared control system with a fixed degree of control sharing that will be called along the paper Lane Keeping Assist (**LKA**).

2. Method

2.1. System overview

2.1.1 Driver monitoring

Despite the obvious need of the driver state assessment for mitigating distraction that is known to be a major cause of accidents (approximately 25% of police-reported crashes involve inattention (Dong et al. 2011) in manual driving, the driver state information is not less important in automated driving. In the considered automation levels (level 1 and level 2) even though released from the control task, the driver retains a central role as he must continuously supervise the system in case he has to regain control of the vehicle. The safety that the automation is meant to offer can be compromised because it may favor driver's distraction and disengagement from the driving task (Merat et al. 2014), hence the importance of driver's inattention detection.

In (Pohl & Westervall 2007) a driver distraction based lane keeping assistance system was presented. The authors argued that driver distraction information provided by a driving monitoring system would be useful in order to decrease false positive interventions which are a source of annoyance in lane keeping assistance systems. In other words, if the driver is detected to be supervising the driving task, the lane departures are more likely to be intentional thus the system is not triggered.

Following a similar idea, a driver supervising the driving scene is more likely to be aware of the road scene and should have the authority over the assistance system. However, if he is detected to be distracted or shows

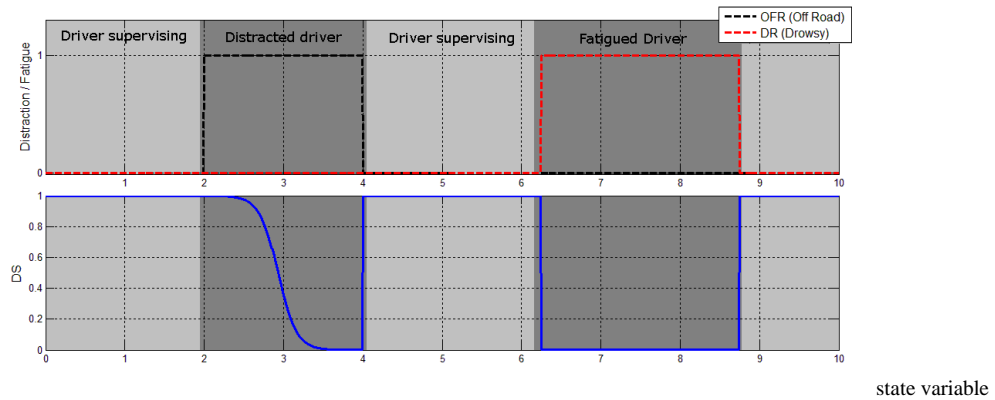


Fig. 1. Driver
($\alpha = 8.5$; $\beta = 8$; $\varepsilon = 0.1$)

low alertness levels, the system may take over. The driver state information can thus be used in the system in order to adapt the assistance to his needs. In fact, when the driver shows distraction or when he is in a state of fatigue, his situation awareness and driving performance are likely to decrease thus the system may increase its authority over that of the impaired driver to maintain the vehicle's safety.

The driver state is related to two main issues: the distraction and the fatigue, and each of them come in several forms. Many methods for assessing the driver state exist (refer to (Dong et al. 2011) for a review).

In our case the driver state information is delivered by an off the shelf driver monitoring system. The Continental driver supervision system (Boverie & Giralt 2008) is based on the real time monitoring of two independent parameters: 1. the fatigue (drowsiness) level obtained by analyzing the driver's eyelids and blinking patterns; and 2. the visual attention deduced from the head position and orientation.

Raw data provided by the driver monitoring system is processed in order to blend the fatigue and visual distraction cues into one single variable called Driver State (*DS*). For the distraction, a binary variable *OFR* (for: Off Road) is available. It takes 0 when the driver watches the road ahead and 1 if he does not.

Another binary variable *DR* (for: DRowsy) takes 1 when the fatigue level is critical and 0 otherwise. *DS* is computed by Eq. 1 (Fig .1).

$$DS = \exp(-DR / \varepsilon) \cdot [1 - (1 + \exp(-\alpha \cdot OFR \cdot T + \beta))^{-1}] \quad (1)$$

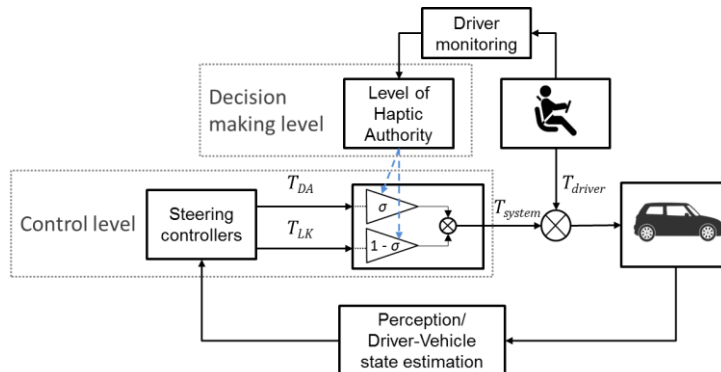


Fig. 2. Adaptive Lane Keeping system architecture

Where: ε is a scaling factor, T is the visual distraction duration, α and β are parameters for modeling the visual distraction. When the driver state is normal, DS equals 1 and decreases towards 0 with the driver state degradation. As shown in Fig. 1, DS smoothly varies from 1 to 0 in the case of distraction but instantly jumps to 1 as the driver gets back to supervising the road (Pohl et al. 2007). DS instantly follows DR to 0 when the fatigue level is critical.

2.1.2 Lane keeping system

a. Architecture

The Lane Keeping System to be tested relies on the control architecture presented in a previous research (Sentouh et al. 2013, Sentouh et al. 2014). It is composed of two hierarchical parts: A decision making level and a control level. (refer to Fig .2).

The latter is based on H_2 Optimal control theory. The design accounts for the steering column model so that the control signal would be the steering torque. Also, by including a driver model, the interactions with the driver are accounted for. The performance vector is a compromise between lateral position error, heading error, lateral acceleration, steering velocity and the torque interferences between the driver and the assistance (We refer the reader to (Sentouh et al. 2013) for the design details).

The final control torque output is a weighted sum of the output of two local optimal controllers designed with different performance objectives as shown in (2).

$$T_{System} = (1 - \sigma) \cdot T_{LK} + \sigma \cdot T_{DA} \quad (2)$$

The first controller, namely Lane Keeping (**LK**), has an objective of minimizing the lane following error and plays the role of a lane keeping system that aims to keep the vehicle on the lane center. This controller is able to drive the car autonomously on a curved road while guaranteeing small lateral positioning errors. According to (Mulder et al. 2012), this controller would correspond to the highest LoHA. It ensures good lane keeping performance (reported in the result section 3.1) but since it has great stiffness around the desired steering command it is less easy for the driver to overrule it and steer away without putting much effort.

The objective of the second controller is set to minimize the torque difference with the driver's and thus behaves quite similarly to a power steering or to a haptic feedback with a negative stiffness as depicted in (Della Penna et. al 2010). As a result, the controller generates a torque that amplifies the driver's steering action making it easier to steer with a reduced effort. This controller will be called Driver Assist (**DA**).

The final system output is a blending of both controllers LK and DA outputs depending on the value of σ . Fig. 3 illustrates the torques when a driver deviates from the lane center. The vehicle lateral trajectory during the driver's maneuver is shown in Fig. 3(a). Fig. 3(b) shows the torque outputs delivered by the local controllers DA (blue), LK (red) and the system's final torque for both values of σ (0,3 green and 0,7 yellow).

As the driver steers away from the lane center, the torque delivered by the LK controller is highly opposed to his action and it would strongly reject any deviation from the lane center. On the other hand DA delivers a torque in the same direction as the driver's which would help him in his maneuver. The system's final output would blend the two local controllers output according to the variable σ (eq. 2). Therefore the more it tends towards zero the system's behavior would lean towards LK's which means an authoritarian assistance that keeps the vehicle in the lane center. This corresponds to the higher end of LoHA. On the contrary, the more σ approaches a value of one which is the lower end of LoHA, the less authoritarian the behavior of the system would be as it can be seen on Fig. 3(b).

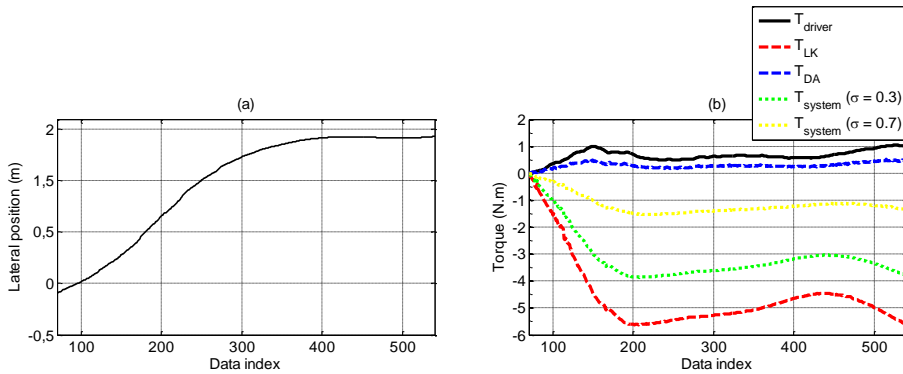


Fig. 3. (a) Vehicle lateral trajectory for a left shift (b) Torques of the driver and the systems during the maneuver

Finally, the decision making level (Fig. 2) gives freedom to define the system operating mode according to the application requirements. It delivers the weighting variable σ used to smoothly manage the haptic authority (LoHA) between the driver and the system. In what follows we describe the design logic of this part for both systems LKA and ALKA.

b. Lane Keeping Assist (LKA)

Continuous haptic feedback with a fixed degree of shared control has already proven to be beneficial in keeping the driver in the loop while improving the lane keeping performance. For this study, in order to set the value of σ and determine the best LoHA for a fixed and continuous haptic feedback, we followed the guidelines in (Abbink & Mulder 2009; Mulder et al. 2012; Mars et al. 2014). A preliminary study following the experimental design in (Mars et al. 2014) has been conducted. The aim was to get a LoHA that offers enough assistance to significantly improve the lane keeping performance while ensuring a good feeling of control instead of a system with overwhelming assistance. This was achieved with a value of σ set to 0,7. This setting yielded an LKA system with a sloppy control when driving without driver input. However, it guaranteed the best compromise between the lane keeping performance and the subjective feelings of comfort and control with a driver actively engaged in the driving task. The lane keeping performance for the LKA driving without driver is reported in the result section 3.1.

c. Adaptive Lane Keeping Assist (ALKA)

As indicated by its name, the ALKA relies on the adaptation of the authority variable σ in real time. It is continuously set according to the driver state and the lane departure risk. When the driver state is normal and there is no departure risk, he would have the authority of driving and manually control the vehicle. In this case, σ tends to 1 and the system output would be mainly the **DA** controller output (refer to Eq. 2). On the other hand, σ tends to 0 when the driver state deteriorates or when a lane departure is imminent, the system takes the authority and the **LK** controller output would be predominant in the system output torque thus showing more authority to keep the vehicle in the center of the lane.

By doing so, the system behaves as and Adaptive Lane Keeping Assist whose output matches the driver state.

2.2. Participants

Fifteen participants (13 males, 2 females) with an average age of 34 ± 10 years took part in the study. They were experienced drivers and had on average 16 ± 9 years of driving experience. They reported an average annual mileage of 19 270 km. None of them was used to writing text messages while driving. The data of two participants were discarded from the analysis due to a malfunction in the driver monitoring system.



Fig. 4. Adaptive Lane Keeping system architecture

2.3. Materials

The study took place on the SHERPA-lamih driving simulator in Fig .4. The simulator is based on a Peugeot 206 mock-up fixed on a six DOF motion system. It is equipped with an active steering wheel and sensors that provide steering angle, steering rate and steering torque.

A force feedback gas pedal as well as a driver monitoring system are installed (These two systems are automotive components provided by Continental Automotive). The visual is displayed on a 240° wide panoramic screen.

The SHERPA-lamih simulator uses the software SCANr by OKTAL that provides a very realistic simulation environment that replicates a rich amount of details of the vehicle dynamics as the self-aligning torque or even the grip of the road related to the road conditions. It offers the possibility to use two development environments: RTmaps (INTEMPORA) and Matlab/Simulink. Simulink being a fast prototyping solution, it was used to implement the algorithms described here above.

2.4. Procedure

The study was conducted on a 4.5 kilometer two lanes one way track. It is composed of a mixture of randomized straight-line sections and left and right curves with different lengths and curvatures. The drivers were instructed to drive on the right lane. There were not traffic vehicles and no lane changes were required during the whole scenario.

Given the focus on the steering behavior, a choice was made to fix the speed in order to avoid issues like variability in the speed choice that might complicate comparisons between the participants, especially when it is known that the steering performance and the speed choice are interrelated (Mulder et al 2012). The driving is thus performed with a cruise control system that regulates at a speed of 70 km/h.

The secondary task consisted on reading and writing a short text message on a 10" tablet during the driving task. The message to copy was on the same text editor window. The proposed texts contained 130 characters with no capital letters nor punctuation to facilitate the assessment of the secondary task performance. The tablet

was positioned on the right side of the driver's seat in such a way that when engaged in the secondary task, he could not monitor the driving scene.



Fig. 5.
Illustration of the test scenario as the drivers arrive on the VMS

The participants were provided with a brief description of the experiment. After they were asked for their consent to take part in the study, they were briefed on the driving simulator and the systems to be tested as well as the security protocols. For each driver, a familiarization phase with the driving simulator was performed. In three different practice runs, they tested manual driving, driving with the LKA and the ALKA systems in the presence of an experimenter to answer the questions they might have. The familiarization took place on a different track and lasted 4 minutes per run. At the end of this phase, the experimenter explained the secondary task. The beginning of the secondary task phase was marked by a variable message road sign (VMS) inviting the drivers to engage in writing the short text message (Fig. 5).

After the familiarization, the study unfolded in three trials. One was performed in manual driving while the others were realized with the LKA and ALKA systems. The order was counterbalanced among the participants. Each trial was divided into two parts: Normal driving task i.e without a secondary task (**No ST**) and driving with a secondary task (**ST**). The text to copy was different for each trial.

For each part, the driving performance was assessed by objective metrics and after each run the drivers filled a questionnaire to report their subjective evaluations.

The first four used objective indicators focus on the lane keeping performance and are commonly used in the literature. The standard deviation of the lateral position (**STDLP** (m)) and the steering wheel reversal rate (**SRR** (s^{-1})) are known to be correlated with visual distraction and heavy cognitive workload (Östlund et al. 2005), a decrease in these two indicators indicates improved driving performance. The mean lateral position (**MLP** (m)) on the other hand, translates the preferred position within the lane and curve cutting behavior. MLP was computed as the distance between the lane center and the center of the vehicle. A negative sign reflects a shift toward the right of the lane center. The MLP is positive for left shifts. Finally, the root mean square of the lateral position error (**RMSE** (m)) was used to characterize the lateral position error with respect to the center of the lane. Moreover, a driver's steering effort (**StE** ($N.m$)²) metric has been used to evaluate the overall effort put by the driver to control his vehicle. It is computed as the integral of the squared driver's torque during a time window of interest which is here represented by each part of the trial. Finally, the secondary task performance (**STP**) was computed by the number of correctly written letters minus the number of mistakes.

For the subjective evaluation, the participants were asked to evaluate the driving according to their feelings of comfort, safety, control quality and workload and report it on a scale from 0 (Worst) to 100 (Best). For each

part a questionnaire was provided and the participants answered on the same sheet for the three strategies (Manual, LKA and ALKA).

For data analysis, a two-way repeated measures analysis of variance (ANOVA) was performed considering two independent variables: the driving task (No Secondary Task, Secondary Task) and the strategy (Manual, LKA, ALKA). The dependent measures are: the SRR, STDLP, MLP, RMSE and StE. For the STP a one-way repeated measures ANOVA was executed. Bonferroni corrections were used as a post-hoc analysis of the results. Results with $p < .05$ are reported as significant.

3. Results and discussions

3.1. Results

3.1.1 Objective results

Fig. 6 depicts the effects of the strategy and the driving task conditions on the lane keeping metrics.

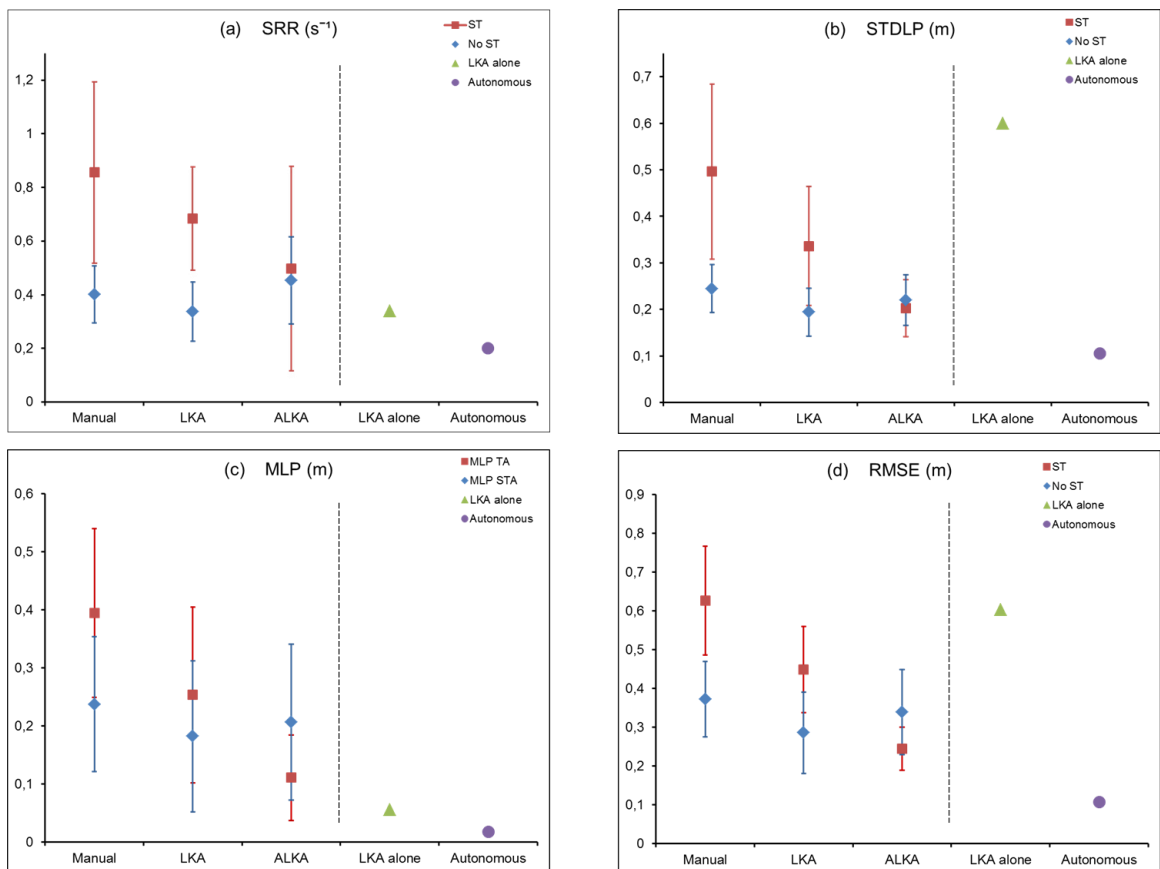


Fig. 6. Objective results: Mean over the participants of the (a) SRR; (b) STDLP; (c) MLP; (d) RMSE and the performance of autonomous driving and the LKA alone. Error bars represent the standard deviation

The steering wheel reversal rate (SRR) results are reported in Fig. 6(a). The means along with the standard deviations are reported for all the driving task and strategy conditions. To the right of the figure are reported the SRR for fully autonomous driving with the LK controller only (refer to section 2.1.2) and for the LKA system alone without the intervention of a driver.

The ANOVA revealed a significant effect of the strategy on the SRR ($F(2,24) = 7,7424$; $p = 0,00254$), a significant effect of the driving task ($F(1,12) = 13,3373$; $p = 0,00331$), and a significant interaction between the two variables ($F(2,24) = 22,7129$; $p < 0,0001$).

During the normal driving task condition (No ST) the LKA strategy yielded the lowest SRR compared to the other strategies (a reduction of 16% compared to Manual). For the ALKA, the SRR was slightly higher than the Manual strategy. However, Bonferroni post-hoc test showed that this difference did not reach statistical significance.

In the secondary task condition (ST) the differences between the three strategies clearly widened (refer to Fig. 6(a)). Under this condition, the SRR increased by a factor of 2 approximately for the Manual strategy. The LKA significantly reduced the SRR relatively to Manual ($p = 0,0116$). Moreover, The ALKA reduced significantly the SRR compared to manual ($p < 0.0001$) and compared to the LKA ($p = 0,0051$).

We highlight the fact that the SRR obtained with autonomous driving was the lowest compared to all other conditions.

The results for the lateral position variability (STDLP) are shown in Fig. 6(b). The ANOVA for this metric also showed a significant effect of the strategy ($F(2,24) = 31,7698$; $p < 0,0001$), a significant effect of the driving task ($F(1,12) = 21,6057$; $p = 0,00056$), and a significant interaction between the two variables ($F(2,24) = 20,2484$; $p < 0,0001$).

The results follow the same pattern as for the previous metric. During No ST condition the LKA yielded descriptively the lowest STDLP compared to Manual (a reduction of 20%) and ALKA which presented roughly similar results. However, post-hoc tests did not reveal statistical significance.

On the other hand, the results under the ST condition revealed significant differences. The lateral position variability nearly doubled for the Manual strategy in this condition compared to normal driving. LKA strategy allowed for a significant decrease of variability relatively to Manual ($p = 0,00027$). In addition, ALKA has proven to be the strategy that reduces the STDLP the most compared to Manual ($p < 0.0001$) and to LKA ($p = 0,00261$). Interestingly, no statistical difference was found between STLD for ALKA under the ST condition and manual driving under normal conditions. Furthermore, we point out the LKA poor performance without driver intervention and that autonomous driving guaranteed the least variability of the lateral position compared to all other cases.

The ANOVA performed on the mean lateral position (MLP) revealed a significant effect of the strategy ($F(2,24) = 16,4130$; $p < 0,0001$). Although the influence of the driving task condition was not found to be significant ($F(1,12) = 2,2093$; $p = 0,162978$), the interaction between the two independent variables reached statistical significance ($F(2,24) = 12,0872$; $p = 0,00023$). Fig. 6(c) presents the results for the different test conditions for MLP. Bonferroni corrections did not establish any statistical difference for the three strategies in the absence of the secondary task despite the clear decrease of the MLP with LKA compared to the other strategies (A reduction of 29% compared to Manual). On the contrary post-hoc tests reported a clear and significant difference between the three strategies when the drivers were engaged in the text writing task. Where LKA resulted in a significant decrease of MLP compared to Manual ($p = 0,00392$), the ALKA strategy has significantly reduced the MLP measure even more compared to Manual ($p < 0.0001$) and to LKA as well ($p = 0,04299$). The LKA when drove alone produced a small MLP and the autonomous setting resulted in a mean lateral position merely close to zero.

The results for the root mean square of lateral error (RMSE) are depicted in Fig. 6(d). The performed ANOVA on this last lane keeping performance metric established a significant effect of the strategy ($F(2,24) = 47,3918$; $p < 0.0001$), a significant effect of the driving task ($F(1,12) = 18,2795$; $p = 0,001078$), and a significant interaction between the two variables ($F(2,24) = 29,8559$; $p < 0.0001$). As for the previous measures, the LKA

yielded the smallest RMSE compared to Manual (a reduction of 23%) and ALKA for the No ST condition. However, these differences did not reach statistical significance.

Furthermore, post-hoc tests confirmed the significance of the clear effects of strategy during the ST condition. As the RMSE increased by nearly 100% with Manual strategy for this condition relatively to normal driving with Manual, ALKA produced the lowest values of the measure comparatively to the other strategies (Manual ($p < 0.0001$) and LKA ($p < 0.0001$)). It is worth noting that LKA also reduced in a significant manner the RMSE compared to Manual in this condition ($p = 0.00022$). Finally, the same trend is noted for the LKA driving by itself which resulted in large trajectory deviations and for the autonomous driving that guaranteed the smallest positioning errors over all the other cases.

Regarding the steering effort (StE), the ANOVA revealed a significant effect of the strategy ($F(2,24) = 8,5727$; $p = 0,00155$), a significant effect of the driving task ($F(1,12) = 39,6123$; $p < 0.0001$), and a significant interaction between the two variables ($F(2,24) = 9,1314$; $p = 0,00112$). The results for the StE are reported in Fig. 7. During normal driving condition (No ST), both LKA and ALKA reduced the steering effort needed to control the vehicle within the lane compared to Manual ($p < 0.0001$ respect ($p < 0.0001$)). They resulted in an effort reduction of respectively 53% and 50%. In the secondary task phase, despite the fact that LKA yielded the smallest value of the steering effort over all the strategies, the difference was only significant relatively to ALKA ($p = 0,00338$). In this condition the ALKA increased the steering effort compared to the other strategies.

Finally, the one-way repeated measures ANOVA performed for the secondary task performance (STP) revealed a significant effect of the strategy ($F(2,24) = 5,3218$; $p = 0,01221$). Fig. 8 reports the results of STP for the three strategies. The best STP was obtained with the ALKA strategy. Post-hoc tests gave the STP with ALKA as significantly higher than Manual ($p = 0,01606$). No statistical differences were reported elsewhere.

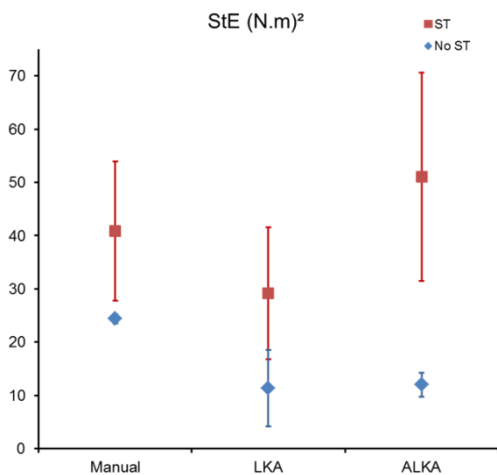


Fig. 7. The steering effort measure for the different conditions. Error bars represent the standard deviation.

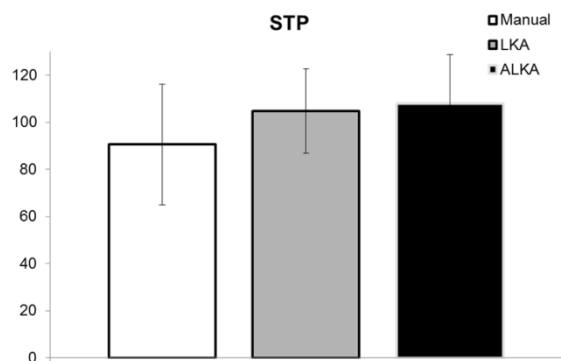


Fig. 8. The secondary task performance. Error bars represent the standard deviation.

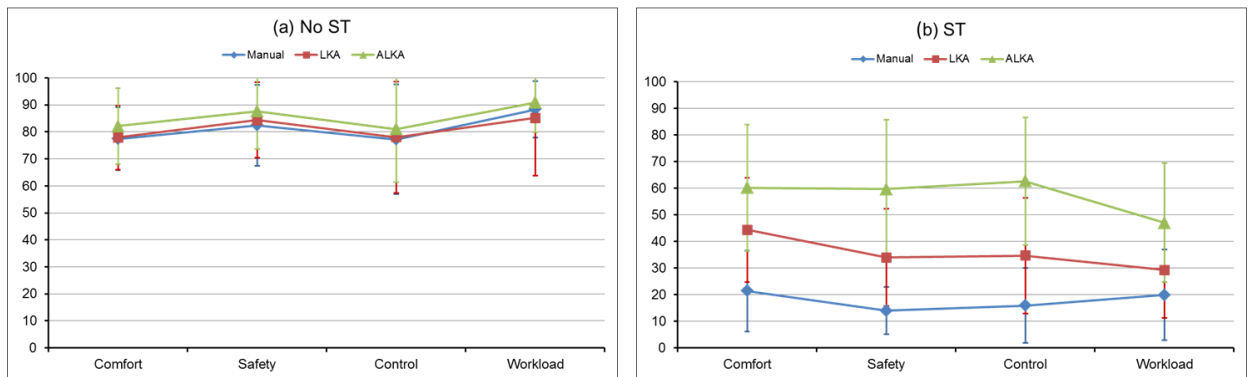


Fig. 9. Subjective results: Comparison between Manual and ALKA (a) in the phase without secondary task; (b) during the secondary task

3.1.2 Subjective results

The subjective results are illustrated in Fig. 9. A two-way repeated measures ANOVA has been performed to study the significance of the subjective results. Significant influences of the strategy, the driving task and the interaction of the two have been found for all the subjective indicators. The results are reported in Table 1.

Post-hoc analysis using Bonferroni corrections has also been performed for additional comparisons. No significant difference over the strategies was noted between the subjective ratings of all the metrics for the No ST condition (Fig. 9(a)). However, the influence of the strategy was marked during the ST condition as depicted in Fig. 9(b). Except for the workload ($p = 0,075275$), LKA allowed for significantly improved feelings of comfort ($p = 0,00042$), safety ($p = 0,00708$) and control quality ($p = 0,00829$) compared to Manual. Within this condition, ALKA improved even more the subjective feelings over all the metrics compared to LKA: comfort ($p = 0,024$), safety ($p = 0,00038$), control quality ($p < 0,0001$) and workload ($p = 0,00152$).

Table 1. Results of ANOVA for the subjective reports

Indicators	Independent variables and their interaction		
	Strategy	Driving task	Interaction
Comfort	$F(2,24) = 20,1434; p < 0,0001$	$F(1,12) = 49,3900; p < 0,0001$	$F(2,24) = 29,7194; p < 0,0001$
Safety	$F(2,24) = 29,7194; p < 0,0001$	$F(1,12) = 77,0649; p < 0,0001$	$F(2,24) = 16,8444; p < 0,0001$
Control	$F(2,24) = 19,5735; p < 0,0001$	$F(1,12) = 40,0937; p < 0,0001$	$F(2,24) = 20,9521; p < 0,0001$
Workload	$F(2,24) = 16,6627; p < 0,0001$	$F(1,12) = 88,7655; p < 0,0001$	$F(2,24) = 12,3063; p = 0,00021$

3.2. Discussions

As expected, the objective results showed that under the normal driving condition and since the drivers were focused on the road ahead, both Manual and ALKA strategies were similar and yielded very close results. The MLP remained the same suggesting that the drivers kept their normal driving behavior with regards to the lateral position in the lane and curve cutting strategy. Within these two strategies all drivers showed a tendency to drive slightly to the left of the lane center. However, ALKA yielded a decrease of the steering effort which relates to the power steering effect of DA controller that amplifies the driver's torque. Furthermore, under this condition, the LKA strategy helped improve the four driving performance indicators, which indicates less variability on the driver's steering actions and on the vehicle's lateral trajectory, a closer positioning towards the lane center and a decrease in the positioning errors. These benefits were obtained along with a reduced steering effort. This suggests that for this driving task condition, the LKA was the best strategy with the delivered continuous fixed haptic feedback. These results are consistent with the findings of previous studies (Mulder et al. 2012, Mars et al. 2014). Consequently, the lesson that this teaches us is that the ALKA's adaptive LoHA should have a lower bound that equals that of the LKA in order to observe the same benefits during normal driving conditions. Which means that in our design, the authority variable σ in Eq. 2 (refer to section 2.1.2) should not exceed 0,7.

Under this driving task condition, the strategy did not influence the subjective results as the ratings of the feelings of comfort, safety and control were roughly the same for all strategies namely: Manual, LKA and ALKA.

More interesting results were noted in the ST condition, on both objective and subjective results.

The objective results showed a significant improvement of the driving performance with the ALKA system and with the LKA to some extent. The STDLP decreased indicating less variability in the lateral position. The MLP on the other hand, revealed that driving with the ALKA during the secondary task helped maintaining the vehicle lateral position closer to the lane center compared to the other strategies. Moreover, dangerous cases of lane departures were noted with manual control. While engaged in the secondary task, some drivers departed from the lane and found themselves driving nearly in the center of the adjacent lane or even on the right road side. No such case happened when the participants drove with LKA and ALKA. Furthermore, LKA significantly reduced the driver's steering effort while the ALKA resulted in a significant increase of the StE. This metric divided the test population in two where it decreased for some participants while it showed notable increase for others with the ALKA strategy. A similar result was reported in (Mulder et al. 2012, Mars et al. 2014) where the steering effort increased when driving with a highly authoritarian level of shared control. This brings up the question of the maximum haptic authority level to leave to the assistance. It is noteworthy that the drivers for whom the StE decreased reportedly showed a more passive behavior towards the ALKA and let themselves be led when engaged in the secondary task.

Moreover, the SRR which is related to a more reactive steering activity reached its lowest with ALKA even though it was also reduced significantly with LKA. However, a larger variability on this metric was observed with ALKA. The noted variability in the behavior towards the system could relate to the difference in adaptation levels between the drivers and the trust they have put in the system. This suggests considering longer familiarization phases (Mcgehee et al. 2004).

Regarding the trust level put in the system, as reported by some participants and underlined in the literature, it may take some time to build up (Beggiato et al. 2013). Among the different behaviors noted according to the trust levels, some drivers relied on the system as they were engaged in the secondary task while others alternated very short glances (less than 2 seconds) between the tablet and the driving scene and therefore did not sufficiently benefit from the system's assistance. In fact, the system did not have the time to fully take control and yielded back the control authority when the driver's looked back at the driving scene. In addition, this highlighted a very sensitive issue in the design of such an adaptive automation. In fact, the mechanism of adapting the assistance is of a great importance and according to their gaze strategies while engaged in the secondary task, drivers benefited in different manners from the system assistance. This is explained by the fact that the authority transition was solely based on the instant distraction due to the driver's visual focus and head

direction, while the cognitive distraction due to the secondary task and a latent distraction that builds during prolonged gaze switching between the driving scene and the tablet were not accounted for. This emphasizes the importance of the information used for authority sharing and an idea for a future research is to include an average visual distraction metric computed on a time sliding window in the authority management algorithm along with other driver performance metrics.

Another factor that might explain the variability of the results might be the engagement level in the secondary task. We have noted that drivers showed different engagement levels. This encouraged the evaluation of the secondary task performance.

The subjective reports in the No ST condition have highlighted the preference of the participants for a more present haptic feedback (provided in the case of the ALKA) during heavy distraction phases. This was also supported by the secondary task scores which were at their highest level when ALKA strategy was used.

Overall, the system in its higher LoHA setting (ALKA during driver distraction) provided the best driving performance, but resulted in negative interactions on the steering wheel as the driver and the system sometimes struggled over the control of the vehicle which significantly increased the driver's steering effort. Interestingly, the haptic feedback in this case which can be felt as authoritarian and intrusive during normal driving conditions appears to be better perceived when the driver's need for assistance increased as a result of a strong distraction related to a the overwhelming secondary task

Furthermore, the studied use case of automation adaptation in this work may encourage drivers to engage in other activities aside from the driving task, which is not tolerated in the current levels of automation given the high risk of failure. However, this behavior is more likely to appear anyway with the increasing levels of automation (Merat et al. 2014). This emphasizes the need for designing effective procedures to tackle the « out of the loop » phenomenon and bring back the driver's attention towards the driving task when distracted for long periods. Nevertheless, this study backs up the idea of considering smooth authority transitions between the automation and the driver rather than abrupt switching when resuming manual control that has already proven to be difficult when drivers were attentive (Hoc et al. 2006 ; Navarro et al. 2016) let alone if they were « out of the loop ». This regains its full meaning when the mutual authority on the driving task is adapted online according to the evolving driving situation, particularly when the driver is distracted, in order to better suit his needs of assistance thus making the assistance less intrusive when not needed.

Finally, the ALKA was often described by participants as « *the passenger who gently acts on the steering wheel when we become distracted* ». The smooth authority shifting was accepted and the participants provided a good feedback on the design paradigm. The latter follows the principles of adaptive automation (Inagaki 2008) and allows the system to change its behavior continuously to match the driver's need of assistance without explicit commands of the driver on the HMI or so. Therefore, instead of having only a lane keeping system that is always active and keeps the vehicle within the center of the lane or only a lane keeping assistance that acts punctually on the steering wheel when a lane departure is imminent, one can take advantage of both design logics at the same time and by smoothly shifting the authority between the driver and the automation the appropriate design is smoothly activated.

4. Conclusion

Continuous fixed haptic assistance has already proven to offer many benefits in many studies. Thus, it was interesting to go further and investigate whether online assistance adaptation according to the evolving situation was relevant in some cases. The present study took place in the SHERPA-lamih driving simulator. It focused on how the ALKA, a system that online adapts its haptic assistance according to the driver's state, would affect the driving performance and safety. It was also meant to bring some insight regarding the acceptance of such a system. For this purpose, a comparison has been made with manual driving as a baseline and with the LKA, a system that provides a continuous but fixed degree of assistance throughout the whole operating period. This comparison has been conducted under two different driving task conditions: Normal driving performing only

the primary task and a secondary task condition where drivers had to write a text message on a tablet installed onboard.

After the general control framework was detailed, the design paradigms of both LKA and ALKA have been exposed. Particularly for the ALKA, the question of importance of authority management mechanisms design as well as the used indicators has been raised.

During normal driving condition the results were consistent with the previous studies that established the benefits of a continuous fixed haptic feedback for lane keeping assistance.

More interesting results were found during the secondary task phase. The evaluation of the driving task revealed that adaptation of the system authority level helped improve the performance when the drivers were engaged in a demanding secondary task. The subjective reports with ALKA have shown a significant improvement of the feelings of comfort, safety, control and workload compared to the other control strategies.

The study revealed that a haptic feedback setting which can be felt as authoritarian and intrusive during normal driving conditions appears to be better perceived when the driver's need for assistance increases as a result of a strong distraction related to a an overwhelming secondary task.

Finally, the feasibility of using the driver distraction provided by a driver monitoring system in order to adapt the assistance to the evolving driver's needs has been demonstrated. However, the use of adequate indicators for adapting the automation remains crucial and should be investigated more thoroughly.

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