Analysis of Human-Machine Cooperation When Driving with Different Degrees of Haptic Shared Control

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Abstract—This study investigated human-machine cooperation when driving with different degrees of a shared control system. By means of a direct intervention on the steering wheel, shared control systems partially correct the vehicle's trajectory and, at the same time, provide continuous haptic guidance to the driver. A crucial point is to determine the optimal level of steering assistance for effective cooperation between the two agents. Five system settings were compared with a condition in which no assistance was present. In addition, road visibility was manipulated by means of additional fog or self-controlled visual occlusions. Several performance indicators and subjective assessments were analyzed. The results show that the best repartition of control in terms of cooperation between human and machine can be identified through an analysis of the steering wheel reversal rate, the steering effort and the mean lateral position of the vehicle. The best cooperation was achieved with systems of relatively low-level haptic authority, although more intervention may be preferable in poor visibility conditions. Increasing haptic authority did not yield higher benefits in terms of steering behavior, visual demand or subjective feeling.

Index Terms—Driving assistance systems, human factors, transportation, shared control, human-machine cooperation

1 Introduction

Continuous progress in the development of automation has led to the design of a variety of driving assistance systems, all aimed at facilitating lateral control of the car. These range from vision enhancement systems to lane departure warning systems, and from partial to full delegation [1], [2]. Recently, a great deal of interest has been directed toward haptic shared control, in which the driver and an automatic controller act and exchange information in a simultaneous and continuous way through the steering wheel (for relevant reviews, see [3], [4]). While this mode of human-machine cooperation appears very promising, determining the degree of sharing that is best for comfort and safety remains an open issue. This paper addresses this question by investigating the effects of several degrees of shared control and driving conditions on various objective and subjective indicators.

1.1 What is Haptic Shared Control?

Haptic shared control can be achieved when an automatic controller use sensors to acquire information about the vehicle and the surrounding environment. From these inputs, it is possible to determine the next best course of action for the driver to take and deliver an adequate amount of torque on the steering wheel to guide the execution of the manoeuver. Following Griffiths and Gillespie's meaningful metaphor [5], it is as if the automatic controller creates a virtual spring between the car and a calculated reference trajectory. Thus, the controller delivers forces on the steering wheel that add to the usual force feedback that comes from the steering system. The additional torque activated by the controller informs the driver that the current steering wheel position differs from the one that the machine estimates to be optimal.

In terms of human-machine cooperation, both the driver and the automaton are autonomous agents that simultaneously share the same control interface, which remains the direct determinant of the vehicle's trajectory. The further the car deviates from the machine's reference trajectory, the stronger is the force experienced by the driver. One should note, however, that an essential property of haptic shared control is that the driver should always be able to override the additional torque. The force gradient and the ease with which the system can be overridden depend entirely on the controller's settings. As such, shared control is distinct from dynamic allocation of control authority between human and machine [6]. With haptic shared control, the level of system intervention may gradually increase, but the level of automation remains the same and the driver is in charge of steering in all circumstances.

The advantages of shared control over manual control have been demonstrated repeatedly. Benefits have been observed in the primary task of lane keeping, as evidenced by improved lateral positioning and steering wheel control [5], [7], [8], [9], [10], [11]. Benefits have also been seen in secondary tasks, with reduced reaction times and workload [5], [7]. It has also been argued that, by keeping the driver in the control loop, shared control may avoid the main pitfall

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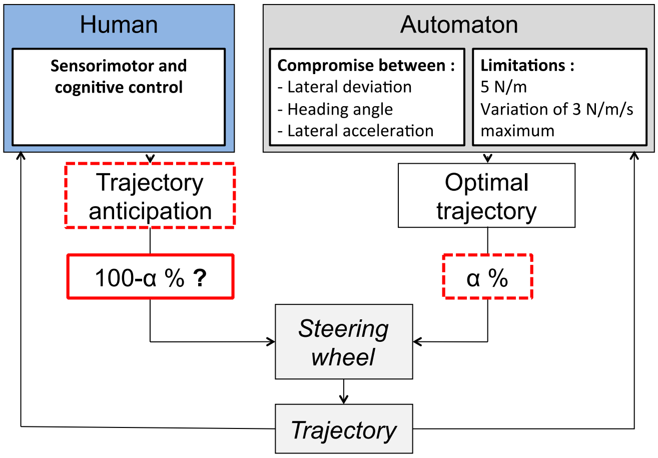

Fig. 1. Illustration of the human-machine system during shared control. The automaton gives α percent of the optimal torque and the driver delivers additional torque $(100 - \alpha$ percent when there is total agreement with the control law). Dotted red lines identify the factors studied (driver's anticipation and level of automated action).

of full delegation, which puts the driver in a supervisory position. Typical issues, such as complacency, skill loss and difficulty to return to manual control, can be avoided. However, longitudinal studies that evaluate how drivers adapt over time to shared control are still lacking [4], [11].

Several issues that have arisen while using shared control systems have also been reported. Obstacle avoidance may be impaired because of a difficulty in overcoming the controller's actions when a large deviation from the centerline is needed [5]. Increased control effort, steering wheel oscillations and a subjective feeling of being "overwhelmed" by the system have also been reported, particularly when associated with a high gain setting of the automatic controller [10], [12], [13]. Indeed, achieving the optimal balance between the system and the driver is a crucial issue in the design of a shared control system.

1.2 What Degree of Shared Control?

In this paper we consider shared control of the steering wheel between the driver and an optimal controller that computes optimal torque for automatic lane keeping. The degree of shared control is determined by how much (α percent) of the torque computed by the control law is actually applied on the steering column (Fig. 1).

The automaton delivers α percent of the torque needed to lead the car along what it considers to be the optimal trajectory. The driver may deliver the theoretical $100 - \alpha$ percent remaining torque when there is full agreement with the system. He may also decide to apply more or less force on the steering wheel when there is partial agreement. If he wishes to disregard the system's suggestion, he may counter the system. The maximum torque applied by the machine is also limited to ensure that the driver can always easily override the system.

This conception may lead to many choices of α percent. Abbink et al. [3] argued that the correct level for the torque delivered by such a device is by far the most important question for designers. They introduced the concept of level of haptic authority and the way it relates to Sheridan's level of automation [14], [15]. Indeed, the setting of α determines how the driver perceives the degree of control that the machine will have on the implementation of action. Taking an empirical approach, it is possible to share control almost equally between human and machine. However other degrees of shared control can be obtained with smaller or higher α. With a very low α, the automation will provide very little haptic guidance; nor will it help much in the execution of the correct action. On the other hand, setting α too high may give rise to a device that is highly authoritarian, so that the driver has to compete for control. Looking only at the performance metrics, lane keeping might be improved, but at the price of discomfort and repeated transient interference.

Thus, it is essential to build a method to evaluate how a shared control system blends into sensorimotor control loops. The present study is aimed at addressing this issue through the analysis of various objective and subjective indicators when driving with different degrees of shared control.

1.3 Shared Control and Visual Anticipation

Another key point is that the optimal allocation of control between human and automaton may depend on the situation, particularly in terms of visibility conditions.

Steering along a winding road relies to a large extent on visual information. It involves short-term compensation of lateral position errors based on near vision, a preview of the road curvature ahead and even more anticipatory look-ahead fixations [16], [17], [18], [19]. Following the publication of Donges' model [20], it has been widely accepted that steering behavior depends on the complementary role of two visual compensatory and anticipatory processes [20], [21], [22], [23]. Using partial occlusion techniques in a simulator, it has been shown that driving with only far vision gives rise to smooth steering behavior; however, large lateral excursions from the center of the road can be observed. Conversely, when only the near part of the road is visible, lane keeping can be maintained, although the control of steering becomes jerky [24]. When visibility is reduced, drivers compensate by, for example, reducing speed and increasing time headway. When time pressure does not allow for this, drivers adopt a more reactive driving strategy in order to be able to react quickly to a critical event. The cost, however, can be measured in terms of mental workload [25].

One question that has never been addressed is whether the optimal repartition of control between human and machine in a shared control system should be the same both in good and poor visibility conditions. If the driver's anticipation capability is reduced, he or she may rely more on a system that more actively guides steering, which may diminish the need to rely on reactive driving. Conversely, the driver may want to retain all capability to react to an unexpected event. In this case, a system with a high level of authority may be judged to be too strong, resulting in impaired cooperation between both agents.

1.4 Visual Demand

Helping drivers to control their vehicle leads to a reduction in visual demand, i.e., how long a driver needs to view the road in order to undertake the driving task safely. [26]. Visual demand is often determined using the occlusion technique. With this method, the driver presses a switch to get a glimpse of the road; otherwise, the road is occluded [27], [28]. Shared control of steering has been demonstrated to reduce visual demand by 29 percent [5]. However, the question that remains to be answered is whether this occlusion technique may be used to determine the optimal degree of shared control. It may be that the greatest reduction in visual demand is obtained with the best lane keeping performance or the highest subjective appreciation of the human-machine cooperation. It may also be that the reduction of visual demand is proportional to the amount of haptic guidance, irrespective of the quality of the interaction. Alternatively, it can be hypothesized that the necessity for the driver to remain in the control loop limits the system's benefits in terms of visual demand, whatever degree of shared control is implemented.

1.5 Aims of the Study

With the previous considerations in mind, an experiment was designed to analyze human-machine cooperation that uses different degrees of shared control. The quality of the integration the guidance forces in the driver's sensorimotor coordination was assessed through the analysis of a set of trajectory and steering wheel variables, and various subjective indicators. The assumption was that shared control would improve human-machine performance up to a point; from thereon negative interference between the driver and automaton may appear. An important objective was to determine the variables that are the most sensitive to the manipulation of shared control settings, which would be useful to a system designer.

Second, we aimed to determine whether the optimal level of shared control depends on the driver's capacity to anticipate changes in road curvature. To this end, human-machine cooperation was assessed both in good and poor visibility conditions.

Finally, using the occlusion technique, we addressed the question of whether the reduction of visual demand that is observed with shared control depends on the amount of haptic guidance.

2 Method

The protocol of this study has been reviewed and approved by the ethics evaluation committee of INSERM (IRB00003888, FWA00005831; decision #12-072).

2.1 Participants

Twenty-one drivers (15 males, Six females, 32 years of age on average) participated in the study. They had all held a driving license for at least two years (mean = 11.6 years). Self-reported annual mileage for the past year ranged from 500 to 20,000 km (mean = 8,690 km). None of them was familiar with lane keeping assistance systems.

2.2 Simulator

The study took place in a fixed-base driving simulator, consisting of a single-seat cockpit with full instrumentation (Fig. 2). It was equipped with a Stirling Dynamics/

Fig. 2. The IRCCyN driving simulator.

TRW Conekt active steering system for realistic "scale one" force-feedback. The SCANeRII software package was used with the CALLAS dynamic vehicle model [29]. The simulator was equipped with a sensor that measured the total torque applied on the steering column. The force feedback calculated by the vehicle model and the assistive torque delivered by the shared control system were subtracted from the measured torque to obtain the driver torque. The visual environment was displayed on three 32-inch LCD monitors, one in front of the driver and two laterals turned at 45 degree from the front one, viewed from a distance of about 1 meter and covering 115 degree of visual angle in width and 25 degree in height. The graphic database reproduced a rural environment. All data were recorded at 20 Hz.

2.3 Experimental Conditions

2.3.1 Varying the Degree of Shared Control

Shared control system may take different forms, using various reference trajectories, path planning algorithms and control strategies [11], [30], [31], [32], [33]. The system used in the present experiment is based on the optimal preview control law described in [34]. This control law is based on an H2 optimization algorithm with a preview of the road curvature, which minimizes a weighted sum of lateral deviation from the centerline, heading angle and lateral acceleration. Moreover, the steering wheel torque was limited to 5 N/m, with a maximum variation of 3 N/m/s. Applied to our simulator setup, the controller was able to autonomously steer the vehicle on the experimental track with a lateral deviation from the centerline of 4 cm on average (measurements made with the SC100 condition described below without any driver input).

Six experimental conditions were studied in this experiment: a control condition (SC00, without assistance) and five distinct levels of shared control (SC01, SC11, SC21, SC31 and SC100). The abbreviation "SCX" means that the torque applied on the steering column is equal to X percent of the torque computed by the control law. It should not be considered as an indication of the repartition of control (expected or measured) between the driver and the automaton. It should also be noted that the percentage values are very specific to our control law and cannot be easily generalized to other implementations of shared control. Thus, the qualitative description that follows is more appropriate for differentiating the different settings of the system.

SC11, SC21 and SC31 represent light, medium and strong settings of shared control between human and machine, respectively. Pretests were carried out using qualitative judgments of the human-machine interaction. They revealed that SC21 was perceived as a condition in which the driver and the system contributed approximately equally to steering. Comparatively, the contribution of the system was judged as markedly lower with SC11 and markedly higher with SC31.

Further explanation should be given about SC01 and SC100. With SC01, the system only delivered minimal haptic guidance. Although the action of the system was continuous, it was only noticeable when the vehicle's lateral deviation was large or when the steering wheel was held lightly. Most often, no sensation of action was felt. Thus, SC01 was introduced to determine whether minimal, nearly subliminal, haptic guidance could be achieved. By contrast, SC100 was used to confront drivers with a very "uncooperative" device, which compensated with force any deviation from the centerline. Thus, the system opposed any willingness to cut curves. In fact, in the SC100 condition, the steering task could be completely delegated to the system, although the participants were not informed of this fact. Since the instruction was the same as in all other conditions, they tried to cooperate with the system. It should be noted that, although the system was very intrusive in this case, it was always possible for the drivers to override its actions because of the maximum torque limitation of the control law.

One may wonder how the system behaves without human interference. Since it delivers only part of the torque required to keep the vehicle on the road, the system acting alone generates trajectories oscillating between the two edges lines as long as the curvature is not too high. If the bend is too severe, the vehicle leaves the road. How much is severe depends on the system setting and the vehicle speed: With a high level of shared control, the system will manage to maintain the vehicle on the road for tighter bends at a given speed. However, it should be stressed that the amount of torque the system delivers entirely depends on the driver's input, and vice versa. Thus, knowing what the two agents do separately is not predictive of the behavior of the human-machine system.

2.3.2 *Varying the Visibility*

All degrees of shared control were tested in three conditions of visibility. In the first condition, good visibility allowed the driver to fully anticipate changes in road curvature. In the second condition, a thick fog reduced visibility (Fig. 3). The fog density was set so that the drivers' vision of the road was fully blocked 50 m ahead of the car. Note that the driving assistance system was not affected by the fog and could anticipate the same way in both conditions.

In order to measure the visual demand of the driving task, with or without shared control, drivers were confronted with another specific situation. In this scenario, the drivers controlled how much visual feedback they received. By default, the simulator screens were black, with one second of vision permitted with each press of the wiper controls. The frequency of request provided a measure of the drivers' need for visual cues.

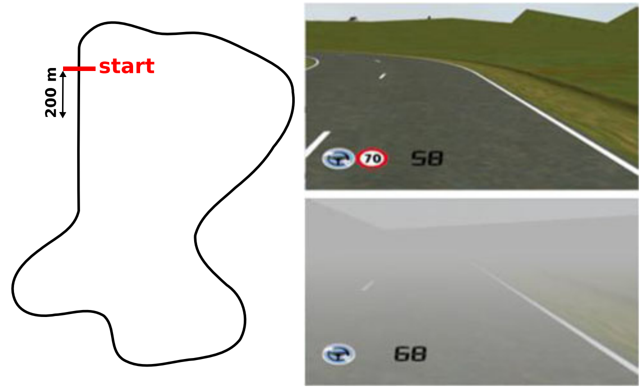

Fig. 3. Schema of the test track (left) and screenshots of the good visibility (top right) and fog (bottom right) conditions. In the screenshots, the blue steering wheel icon was an indicator of the activation of shared control. A digital speedometer and an occasional speed limit sign were displayed in order to assist the drivers in their compliance with the speed instruction.

2.4 Procedure

After the participants were installed in the simulator, they were briefly instructed in the principle of shared control. It was emphasized that the system was unable to drive by itself and that continuous driver action was needed to steer the car. The participants were told that they would be asked to drive with different system settings. The only general instruction was to comply with speed limits (70 km/h) and drive as they would do in real life. In order to help them comply with this instruction, a digital speedometer was provided on the visual scene. Moreover, a speed limit sign appeared when they were not driving between 65 and 75 km/h. In addition, when shared control was activated at speeds of 30 km/h or more, an indicator was displayed to confirm this activation.

The experiment started with a 10 minutes familiarization drive, which is more than enough time for the participants to get used to the driving simulator and for steering behavior to stabilize [35]. Then, the participants completed the three visibility scenarios (good visibility, fog and visual demand) with each modality of the assistance factor. The order of presentation of the conditions was randomized. Thus, in the experiment, all drivers were asked to perform 18 complete laps of a 2.5 km long country road made up of a mixture of curved and straight-line sections (Fig. 3). The driving lane was 3 m in width; it was delineated with a broken centerline and an edge line. Other vehicles were simulated occasionally in order to encourage participants to remain in their own lane.

For each modality of the assistance factor, drivers completed a brief questionnaire. They were asked to evaluate the effect of shared control on comfort, safety, control of the situation and attention allocated to driving in comparison with driving without assistance. The participants had to position themselves on a 10-cm analogical scale from "full disagreement" to "full agreement" for each of the following items:

- Comfort: "Driving with this assistance system was comfortable."
- Safety: "Driving with this assistance system improved safety."
- Control: "I felt I had the situation under control."
- Attention: "I could pay less attention to driving."

2.5 Data Analysis

Four indicators of steering wheel and trajectory control were computed for both the good visibility and fog conditions.

In order to assess the stability of steering wheel control, the steering wheel reversals rate was computed as: $\mathrm{SWRR} = nb/T$; in which nb = number of changes of direction in steering wheel rotation over one lap and T = duration of the lap (in s). The effort requirement for maintaining the vehicle in the lane over one lap (steering effort) was computed as the sum of the square of the steering torque: $\mathrm{SEf} = \int_{t=0}^{T} \Gamma_d^2 dt$, with Γ_d the driver's torque expressed in N.m, and SEf in $(\mathrm{N.m})^2$.s.

The trajectory produced by the human-machine system was summarized by the mean lateral position during bends (MLP) and the standard deviation of the lateral position over the lap (SDLP). MLP was computed as the distance between the lane center and the center of the vehicle. Data for right bends were inversed and regrouped with the data for left bends in order to obtain an indicator of the tendency to cut the corner irrespective of the bend direction.

In the visual demand condition, the frequency of visual request (fVR) only was analyzed. It was computed as the number of wiper control presses over one lap divided by the duration of the lap.

For all statistical analyses, the significance level was set at .05. Two-way repeated measures analyses of variance (ANOVA) with visibility (good visibility versus fog) and the degree of shared control (SC00, SC01, SC11, SC21, SC31, SC100) as independent variables were performed on SWRR, SEf, MLP and SDLP. For both visibility conditions, Dunnett's tests were used to compare each of the conditions with assistance to SC00, considered as the baseline condition. Additional comparisons were performed using Bonferroni corrections. For fVR, a one-way repeated measures ANOVA with the degree of shared control as the independent variable was used. For each item of the questionnaire, one-way repeated measures ANOVAs were also performed, but with only five degrees of shared control this time.

3 Results

3.1 Steering Wheel Indicators

Fig. 4 represents the effects of shared control level and visibility on the steering wheel measures.

The ANOVA reveled a significant effect of the degree of shared control on SWRR ($\mathrm{F}(5,70) = 14.64, \mathrm{p} < 0.001$), a significant effect of visibility ($\mathrm{F}(1,14) = 15.32, \mathrm{p} < 0.001$) and a significant interaction between the two variables ($\mathrm{F}(5,70) = 5.38, \mathrm{p} > 0.001$). In the two visibility conditions, all shared control settings except SC100 descriptively reduced the SWRR. When visibility was good, this reduction was significant only for SC11 ($\mathrm{p} < 0.05$). In fog, the reduction of SWRR compared with the control condition was markedly higher and reached statistical significance when using SC11, SC21 and SC31 ($\mathrm{p} < 0.001$ in all cases). The largest gain was observed with SC21, but the difference with SC11 and SC31 was not significant. On the other hand, SC100 increased SWRR in comparison with SC00. The difference was significant in the good visibility condition ($\mathrm{p} < 0.001$), but not in the fog condition.

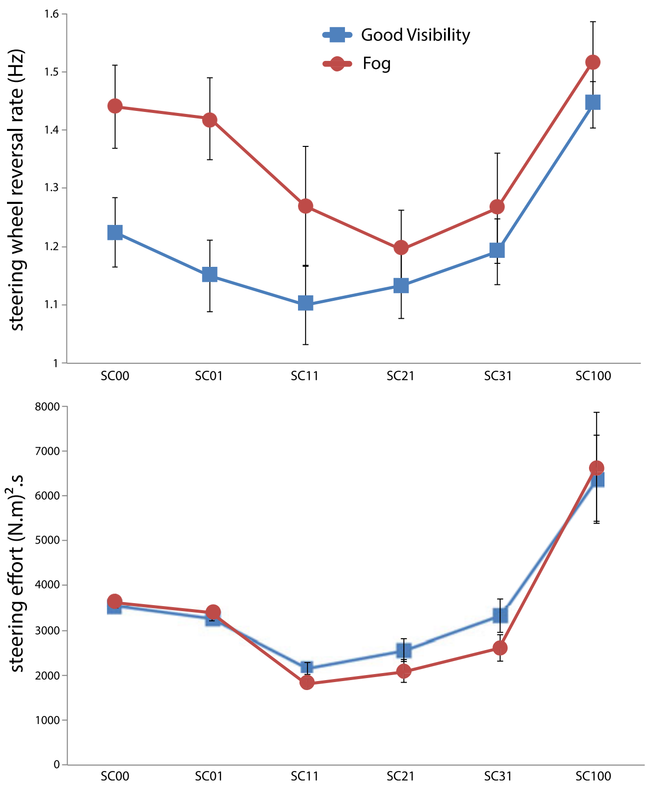

Fig. 4. Steering effort (top) and steering wheel reversal rate (bottom) as a function of the degree of shared control and visibility. Error bars represent standard errors of the means.

Applied to the steering effort data, the ANOVA showed a significant effect of degree of shared control ($\mathrm{F}(5,70) = 14.64, \mathrm{p} < 0.001$), but no effect of visibility ($\mathrm{F}(1,14) = 0.67$) and no interaction ($\mathrm{F}(5,70 = 0.58)$. Descriptively, when the results of the two visibility conditions were averaged, SC01, SC11, SC21, SC31 reduced the steering effort by 7, 45, 35 and 17 percent, respectively. Dunnett's tests revealed that steering effort was significantly reduced only with SC11 ($\mathrm{p} < 0.05$). Moreover, SC100 caused an increase in steering effort of 81 percent ($\mathrm{p} < 0.001$). This demonstrates that the drivers competed with the automaton for control of the steering wheel, in accordance with the observed increase in steering wheel reversals. Finally, it appears that the fog slightly decreased the steering effort with SC11, SC21 and SC31; however, post-hoc analyses showed that these differences did not reach statistical significance.

3.2 Trajectory Indicators

Fig. 5 represents how visibility and shared control level influenced vehicle trajectory.

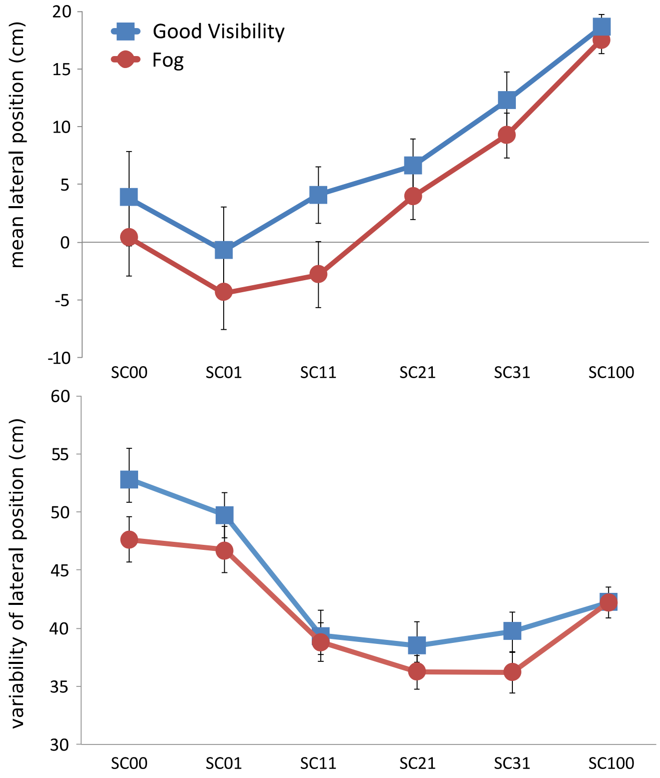

Fig. 5. Mean lateral position in bends (top) and variability of the lateral position (bottom) as a function of the degree of shared control and visibility. Error bars represent standard errors of the means.

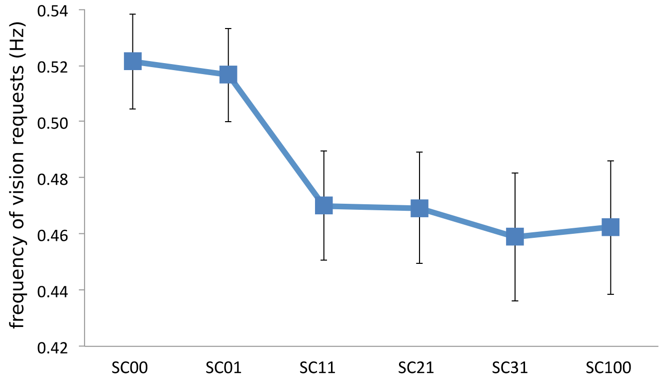

Fig. 6. Frequency of visual requests as a function of the degree of shared control. Error bars represent standard errors of the means.

Without shared control, the participants showed a slight tendency to cut the corner when negotiating bends, which is a commonly observed behavior [36], [37], [38]. The ANOVA revealed a significant effect of the degree of shared control on the MLP ($F(5, 70) = 30.93, p < 0.001$), a significant effect of visibility ($F(1, 14) = 6.51, p < 0.05$), and no significant interaction between the two variables ($F(5, 70) = 0.91$, ns). Whatever the visibility condition, Dunnett's tests yielded the same results. They showed that SC01, SC11 and SC21 did not significantly influence the MLP. However, with stronger settings (SC31 and SC100), the drivers drove significantly closer to the inner edge line than when driving without assistance ($p < 0.001$ in all cases). One should bear in mind at this point that without any action of the driver on the steering wheel, SC100 would have maintained the vehicle very close to the lane center and SC31 would have undercompensated for road curvature. Thus, the increased corner-cutting tendency observed with these settings was not determined by the automation proper, but by the interaction between human and machine.

The ANOVA performed on SDLP revealed a significant effect of the degree of shared control ($F(5, 70) = 33.63$, $p < 0.001$), a significant effect of visibility ($F(1, 14) = 8.90$, $p < 0.01$), and no significant interaction between the two variables ($F(5, 70) = 1.86$, ns). On average, SDLP was smaller when driving in fog compared with the good visibility condition. Whatever the visibility condition, the shared control system reduced SDLP for all settings with the exception of SC01 ($p < 0.001$ in all cases, except SC00 versus SC100 in fog: $p < 0.005$). Additional Bonferroni post-hoc tests showed no significant difference between SC11, SC21, SC31 and SC100 in the good visibility condition. In fog, however, SDLP increased with SC100 in comparison with SC21 and SC31.

3.3 Visual Demand

In the visual demand scenario and when shared control was inactive (SC00), fVR was 0.52 Hz, on average (Fig. 6). Given that a request gave one second of vision, this means that participants drove about half the time without being able to see the road ahead. The ANOVA showed that the degree of shared control had a significant effect on fVR ($F(5, 70) = 8.23, p < 0.001$). Dunnett's tests showed no effect of SC01 and a significant reduction with SC11 ($p < 0.005$), SC21 ($p < 0.005$), SC31 ($p < 0.001$) and SC100 ($p < 0.001$). Those four conditions did not differ from each other. Thus, SC11 reduced visual demand by about 10 percent in comparison with SC00; however, almost no additional gain was obtained with a stronger intervention of the automaton.

3.4 Subjective Assessment

As shown on Fig. 7, the degree of shared control significantly influenced the response to all items of the questionnaire (comfort: $F(4, 56) = 5.59$; control: $F(4, 56) = 9.17$; safety: $F(4, 56) = 6.08$; attention: $F(4, 56) = 8.27, p < 0.001$ in all cases). Because of the large interindividual variability

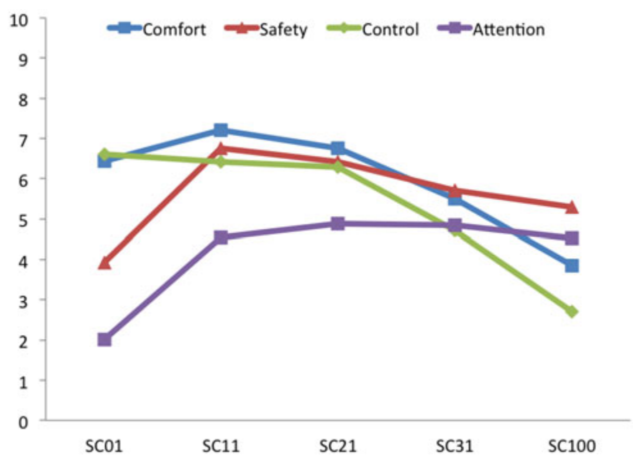

Fig. 7. Subjective comparison between shared control and driving without assistance in terms of comfort, safety, control feeling and attention to steering.

associated to subjective reports and the size of the population sample, the pairwise comparisons did not reach statistical differences, except when noted.

Comfort and a feeling of control present very similar patterns. SC01, SC11 and SC21 were rated fairly close. With SC31, ratings started to drop, although the difference was not significant. With SC100, the loss in comfort and feeling of control increased and reached statistical significance (comfort: $p < 0.01$; control: $p < 0.001$).

When asked about how the system improved safety, the participants rated SC01 below the mid-value of the scale. SC11 gave rise to a large and significant improvement ($p < 0.001$). The sense of safety gain slightly decreased with each degree of shared control, but this reduction was not significant. However, when SC31 and SC100 were compared with SC01, the difference was no longer significant.

Finally, when drivers had to report whether they could pay less attention to driving when using the system, SC01 was rated very low in comparison with the four other settings ($p < 0.001$ in all cases), which did not differ from each other. This result mirrors the one observed on fVR.

4 Discussion

The present experiment investigated how the lateral control of a vehicle was affected by different settings of an automatic controller that shared control of the steering system with the driver. The experiment was carried out in good visibility conditions, when driving in dense fog, and with self-controlled occlusion of the visual scene. In summary, the results showed that:

1. An optimal repartition of control in terms of human-machine cooperation can be determined through the analysis of several variables, with the SWRR indicator being particularly sensitive;
2. In low visibility conditions, drivers benefit more from shared control and the optimal level of haptic guidance may be slightly higher than in good visibility conditions;
3. The reduction of the visual demand of driving is independent of the amount of haptic guidance delivered by the system.

In the following discussion, we will address the significance of these results, how they relate to the concept of haptic authority and the ergonomics recommendation that can be drawn from them.

4.1 Human-Machine Cooperation as a Function of Haptic Authority

First, it has to be noted that the weakest level of intervention of the shared control system (SC01) did not significantly influence any of the performance indicators. This level of shared control was set so that the action of the system was minimal, just above the perceptual threshold but with no direct influence on vehicle control. This was obviously not enough to help the driver to steer the vehicle. By contrast, low and intermediate levels of shared control (SC11 and SC21) markedly reduced SWRR, SEf and SDLP, while no change was observed to MLP. This suggests that the action was well integrated into the sensorimotor control loop of the driver, who remained on the same path but with a smoother steering activity. At the subjective level, drivers reported they felt in complete control and judged driving to be safer and more comfortable than when driving without assistance.

When using SC31, drivers continued to benefit from the system, but to a lesser extent, especially in the good visibility condition. In this case, SDLP remained as low as with SC11 and SC21, although SWRR and SEf values were close to those observed in the control condition. Moreover, the vehicle path deviated in the direction of the inner edge line; that is to say, in the opposite direction to the reference trajectory of the system. This suggests that drivers started to come into conflict with the system, rather than accepting the path promoted by the controller. The appearance of cooperation problems is confirmed by subjective ratings. Although the system was still perceived to improve safety, there was a reduction in feeling of comfort and being in control. All these cooperation issues were amplified with SC100, which should be considered as the reference condition for evaluating human-machine conflict (see Section 4.3).

These results suggest that the quality of the cooperation between human and automation is related to the question of who has authority in the execution of the steering task. Authority sharing is a classic issue in human-machine interaction [39]. When operational control is completely delegated to the machine, the question is most often which of the two agents, human or automaton, should have the final word in the decision process (i.e., the distinction between soft and hard automation in aircraft piloting [40]). When the operator can or must resume manual control, the problem becomes how to achieve the transition between assisted and non-assisted control. With shared control, there is no such issue: the driver is always involved in the operational control of the vehicle and can override the action of the system in all circumstances. Thus, there is no conflict of authority in the traditional sense. However, the system continuously delivers a physical force that translates to the driver as a level of guidance. This relates to the concept of haptic authority proposed by Abbink et al. [3]. In this case, the level of authority corresponds to the persuasiveness of the system is rather than which of the two agents has the final word, because the system has been designed to always yield to the driver. Nevertheless, a high level of haptic authority may lead to confusion and conflict over who is in charge of steering. Ultimately, the driver is placed in a position where he must choose between complying with the machine's pressing suggestion or "disobey".

Within the shared control paradigm, the question of the relationship between shared control and shared authority is central. Our results show that drivers clearly wished to maintain authority, even with the strongest level of automaton intervention, which translated as conflict between the two agents. Since the largest performance improvements were obtained with a low level of haptic guidance, this suggests that designers should look at how much guidance is just enough to help the driver rather than at how much force can be tolerated by the driver. In the former case, haptic authority is unequivocal, which may be an essential criterion for system acceptance.

On the other hand, the best repartition of control between human and machine may depend on the ability of the system to predict the driver action. In the ideal case in which the prediction is perfect, negative interference due to prediction errors would disappear. The greatest benefits in that case may be obtained with a high level of haptic authority. The question for designers would then become: what is the minimum part of control the driver should retain to remain into the loop? Perfect prediction of driver behavior is still far from our grasp, but some advanced steering control model have been proposed. It has recently been suggested that integrating a driver model to the design of control law may improve shared control [41], [42], [43], [44]. It should be added that it might also allow higher level of haptic authority without creating negative interference.

4.2 Shared Control and Vision of the Road

When driving in thick fog, drivers lost some of their ability to anticipate changes in road curvature. This yielded more reactive steering behavior, which most notably translated as an increase in SWRR. When drivers benefited from the assistance system, the difference in SWRR between the good and poor visibility conditions diminished a great deal. Actually, based on this variable, one could say that the benefits of shared control are much greater in poor visibility conditions than in normal driving conditions. The results also suggest that the optimal repartition of control between human and machine may not be the same in the two situations. Indeed, the maximal reduction of SWRR in the good visibility condition was obtained with SC11, whereas SC21 gave rise to the largest improvement when driving in fog. Together with the fact that the drivers produced slightly less steering effort when driving with the shared control system in fog, it appears that they relied more on the guiding forces than with full visibility. This demonstrates the potential of shared control systems for driving assistance, because drivers readily accepted haptic guidance when driving conditions became difficult.

In the occlusion scenario, the shared control system reduced the need for road vision, as reported in previous studies [5]. However, visual demand decreased by 10-12 percent, far below the 29 percent improvement reported previously. Varying degrees of difficulty of the test track may explain this difference. Whatever the case may be, the most interesting result is that visual demand remained constant between the different degrees of shared control. At the subjective level, drivers also reported that they could not pay less and less attention to the road with increasing haptic guidance. This goes against the idea that the need for a road preview decreases proportionally to the amount of assistance received by the drivers. Shared control may offer the opportunity to disengage to some extent from road monitoring; however, since the driver must remain in the control loop, this disengagement appears to be limited.

4.3 How to Measure the Quality of Shared Control

Trying to capture the quality of driving by means of a limited set of descriptive variables can sometimes lead to erroneous conclusions. Cross-checking various indicators should always be favored. In the present study, human-machine cooperation was assessed through the analysis of five performance indicators and four subjective ratings. One methodological objective of the study was to determine the coherence between those variables and to identify those variables that are most sensitive to the manipulation of the shared control setting.

Out of the five performance indicators, the SWRR was clearly the more discriminating, as it was highly sensitive to the manipulation of both shared control level and visibility. SWRR is a good indicator of the stability of steering control. It has been showed to increase with cognitive load and task demand [45], [46], enhancement of the visual scene [17] or driving experience with a simulator [35], for instance. The cumulative steering effort was also influenced by the degree of shared control, although the effect of visibility was tenuous. To capture cooperation conflicts, it may be preferable to compute more transitory torque variations rather than the global indicator that we used.

The SDLP is one of the usual indicators of lane keeping performance. Yet, it did not offer much information about the quality of human-machine cooperation. Indeed, all settings of the system reduced the variance of lateral deviation, even the obviously intrusive SC100 setting. However, it should be noted that SDLP was larger with SC100 than with the other settings. This difference was significant in the fog condition. This suggests that SLDP can indicate human-machine conflicts, although to a limited extent. A similar conclusion on the lack of sensitivity of the visual demand indicator, at least when using the self-controlled occlusion method. On the other hand, MLP may inform on a conflict between the automaton and the driver, because it remained unchanged for all moderate settings of the systems but significantly deviated with SC31 and even more so with SC100.

It comes as no surprise to learn that subjective assessments of the system's quality gave rise to a larger interindividual variability than did performance measures. However, the pattern of results was entirely coherent with conclusions drawn from the observation of driver behavior. It is not trivial since it has been repeatedly demonstrated that systems can be judged poorly, even though they improve user performance [47], [48]. In the present case, improvements in steering behavior unequivocally translated as an increase in comfort and a feeling of control.

Before concluding, it is important to remind that if the relative validity of simulator studies is often quite good (i.e., the observed pattern of results for a given experimental manipulation is qualitatively similar in a simulator and real car studies), their absolute validity is not assured (identical numerical values may differ) [49]. The relative sensitivity of indicators to shared control settings might be different when the system is implemented in a real car. Finally, the time-to-line crossing (TLC) has been demonstrated as a sometime useful indicator of steering behavior and how steering relates to the driver's safety margins [50], [51]. It has not been computed in this study, but it may be considered to evaluate shared control systems.

5 Conclusion and Perspectives

This study investigated how drivers cooperated with different levels of intervention of a shared control system. It offered some methodological recommendations on how to determine the optimal repartition between human and machine. In addition, it showed that drivers favored systems that have a relatively low level of haptic authority. In this study, it was also demonstrated that shared control was more of a benefit to the drivers in low visibility conditions; in that case, slightly more haptic guidance may be delivered.

Further studies are now required to determine how these results can be generalized to other shared control designs and other situations. Also, as interesting as it may seem, adjusting the degree of shared control to match the situation may not be without problems. Drivers may become confused if the degree of shared control changes with the context. Here, one solution may be to deliver appropriate feedback to the driver on the way the automaton acted.

It should also be noted that the shared control system implemented in the driving simulator was entirely reliable. Although there exist hardware and algorithms to compute all the necessary inputs in real cars, inaccurate or noisy sensors might impair the reliability of the system. This may influence the driver's trust in the system and, in turn, how drivers accept to share control with the system.

Finally, longitudinal studies of how drivers adapt to shared control systems are still lacking. It would be particularly interesting to assess whether the optimal repartition of control between human and machine changes as experience of using the system grows.

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