

Obstacle Avoidance in Highly Automated Cars: Can Progressive Haptic Shared Control Make it Safer and Smoother?

Béatrice Pano , Philippe Chevrel , Fabien Claveau , Chouki Sentouh , and Franck Mars , *Member, IEEE*

Abstract—Haptic shared control has proven to be an effective method to assist a driver in controlling a vehicle. This method is now being considered for use in developing strategies for smooth transitions between manual and autonomous driving modes. This article has two objectives. First, it proposes to adapt an existing haptic shared control strategy to achieve transitions between manual and autonomous modes and to evaluate this approach with real drivers on a driving simulator. Second, it proposes to evaluate four different transition profiles in an obstacle-avoidance context. The first profile is a gradual transition from the autonomous mode to shared control mode, followed by another transition from the shared control mode to autonomous mode once the obstacle is passed. The second is a gradual transition from autonomous mode to manual mode. The third is a binary transition from autonomous mode to manual mode. Finally, in the fourth condition, the driver overrides the autonomous mode. These transition profiles were evaluated in curves and straight lines on a driving simulator. The results first validated the use of the haptic shared control strategy to execute transitions between manual and autonomous modes. The distribution of the torques delivered by the automation system and the driver corresponded to the progression of the expected sharing level. Second, the gradual transitions showed advantages over binary transitions and the override of the autonomous mode, both in terms of steering performance and subjective evaluation.

Index Terms—Autonomous vehicles, driver behavior, haptic control, human–automation interaction, multiobjective (H_2/H_∞) control.

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I. INTRODUCTION

IN RECENT years, the development of autonomous vehicles has become a major interest for car manufacturers. As human error remains the primary factor in the number of car accidents [1], the autonomous vehicle can be considered as a means of improving road safety [2]. However, in the early stages of autonomous vehicle deployment, the driver will still need to be able to regain control because vehicles will not be able to handle certain complex or unexpected situations. Therefore, the question of transitions between autonomous and manual driving is a central issue in the development of the next generation of vehicles.

The transition from autonomous driving to manual driving is a critical phase. The driver needs to be aware of the driving situation in order to regain control properly, as the driver’s workload suddenly increases during the transition [3]. However, the higher the previous level of automation, the less attentive the driver may have been to the road before the takeover request, especially if they were involved in secondary tasks [4]–[7]. The reason for this inattention is that drivers may become complacent with the autonomous system, which works well most of the time. The reduction of the driver’s attention to the road may lead to a decrease in the ability to regain manual control [8], [9]. Therefore, in order to achieve good recovery performance, the drivers need sufficient time to regain situational awareness. In addition, after a phase of autonomous driving, the driver needs to restore eye–steering coordination and recalibrate the sensorimotor loops involved in the control of the actuators [10]. Therefore, research is being conducted to determine which modalities are most relevant for smooth transitions [11]–[13].

Haptic shared control (HSC) could be a satisfactory solution to manage transitions [10], [14]. In HSC, to avoid abrupt transitions and to switch gradually from one driving mode to the other, autonomous driving and manual driving can be connected through a phase in which the driver and the automation system share the steering wheel [15]. When used as a driving assistance system, the HSC has been shown to reduce the driver workload and increase vehicle stability [16]. Several HSC strategies have been proposed in the literature to achieve transitions [17]–[19]. In [19], a comparison of different transition profiles using HSC was evaluated in a context of takeover request initiated by the machine in the lane-following task. The study shows the benefit of using a gradual transition in such a case as the results are

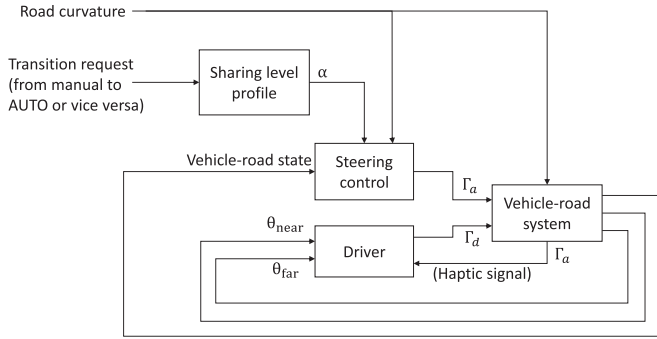


Fig. 1. Shared control-based transition principle.

better in terms of lane-following performance as well as driver acceptance.

The objective of this study is twofold. First, it proposes to adapt the HSC strategy presented in [20] to the problem of transitions and to implement it in a driving simulator for evaluation with real drivers. Second, an experiment was conducted to compare different transition profiles in order to determine their potential usefulness. Four transition profiles were assessed in the context of obstacle avoidance, in both curves and straight lines. Two of these transition profiles involve transitions from autonomous mode to manual mode: a gradual linear transition and a binary transition. The other two profiles end in autonomous mode. The first of the other two profiles is a gradual transition from autonomous driving mode to HSC of the steering wheel that lasts a few seconds before returning to autonomous mode. The second remains in autonomous mode for the duration of obstacle avoidance with the possibility for the driver to override the system.

The rest of this article is organized as follows. Section II presents the HSC strategy used and how it has been adapted to achieve progressive transitions. Section III presents the whole experimental procedure. It contains a description of the equipment used, the participants, the experimental procedure, and the indicators that will be used to analyze the results. The results are described in Section IV. Finally, Section V concludes this article.

II. TRANSITION BETWEEN MANUAL AND AUTONOMOUS DRIVING USING HAPTIC SHARED CONTROL

In order to achieve progressive transitions between manual and autonomous driving, the use of an HSC strategy is proposed. Fig. 1 illustrates the principle of the solution investigated in this article. The steering control system (respectively the driver) is driving alone in autonomous (respectively manual) driving. In case of a request (from the driver or from the system according to the environment), the level of sharing gradually changes to autonomous or manual driving. This section first introduces the driver-vehicle-road model used for control synthesis and associated signals, and then the control strategy.

A. Description of Models

The control strategy designed in the current work is based on two models: a vehicle-road model and a driver model. The vehicle-road model represents both the vehicle dynamics and

TABLE I
VEHICLE-ROAD MODEL PARAMETERS VALUES

l_f	Distance from gravity center to front axle	1.289m
l_r	Distance from gravity center to rear axle	1.611m
m	Total mass of the vehicle	1834.9kg
J	Vehicle yaw moment of inertia	2800kg.m ²
C_{f0}	Front cornering stiffness	64807N/rad
C_{r0}	Rear cornering stiffness	68263 N/rad
η_t	Tire length contact	0.245m
ν	Adhesion	0.8
K_m	Manual steering column gain	0.031
R_s	Steering-gear ratio	14.54
B_s	Steering-system damping coefficient	1.0173
I_s	Inertial moment of steering system	0.0891kg.m ²
μ_s	Spring stiffness	0.9141N.m/rad
l_s	Look-ahead distance	5m
V_x	Longitudinal speed	18m.s ⁻¹
D_{far}	Distance to the tangent point	15m

its position on the road using for a given longitudinal speed. It can be written as follows:

$$\dot{x}_{vr} = A_{vr}x_{vr} + B_{1vr}(\Gamma_a + \Gamma_d) + B_{2vr} \begin{bmatrix} F_w \\ \rho_{ref} \end{bmatrix} \quad (1)$$

with

$$A_{vr} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & \frac{b_1}{R_s} & 0 \\ a_{21} & a_{22} & 0 & 0 & \frac{b_2}{R_s} & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ v_x & l_s & v_x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{T_{s\beta}}{I_s} & \frac{T_{sr}}{I_s} & 0 & 0 & -\frac{T_{s\beta}}{R_s I_s} - \frac{\mu_s}{I_s} & -\frac{B_s}{I_s} \end{bmatrix} \quad (2)$$

$$B_{1vr} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{I_s} \end{bmatrix}, B_{2vr} = \begin{bmatrix} e_{11} & 0 \\ e_{22} & 0 \\ 0 & -v_x \\ 0 & -l_s v_x \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (3)$$

where Γ_a and Γ_d are the assistance and the driver torque applied on the steering wheel, respectively, ρ_{ref} the road curvature, and F_w is the wind force resultant applied on the vehicle. The vehicle-road state vector is defined as $x_{vr} = [\beta \ r \ \psi_L \ y_L \ \delta_d \ \dot{\delta}_d]$, where β is the slip angle, r is the yaw rate, ψ_L is the heading error angle, y_L is the lateral deviation between the vehicle and the lane center at a look-ahead distance l_s , and δ_d is the steering wheel angle. Coefficients a_{11} , a_{12} , a_{21} , a_{22} , b_1 , b_2 , $T_{s\beta}$, T_{sr} , e_{11} , and e_{22} are described in [21]. Vehicle-road model parameter values are given in Table I.

The use of a driver model is recommended to design an HSC acting in synergy with the driver. This reduces conflicts between the assistance system and the driver and improves driver acceptance [22], [23]. The driver model used in this document is the one proposed by [23]. This cybernetic driver model has two inputs: the angle to a near point θ_{near} , and the angle to a far point θ_{far} . These two points represent the use of visual information by drivers to compensate for lateral positioning errors and to anticipate changes in the road curvature, respectively [24]. The

TABLE II
 DRIVER MODEL PARAMETERS

K_p	Anticipation gain	3.4
K_c	Compensation gain	15
T_I	Compensation frequency band	1
T_L	Compensation rate	3
τ_p	Human processing time delay	0.04
K_r	Steering column stiffness	1
K_t	Steering-wheel holding stiffness	12
T_N	Neuromuscular time constant	0.1

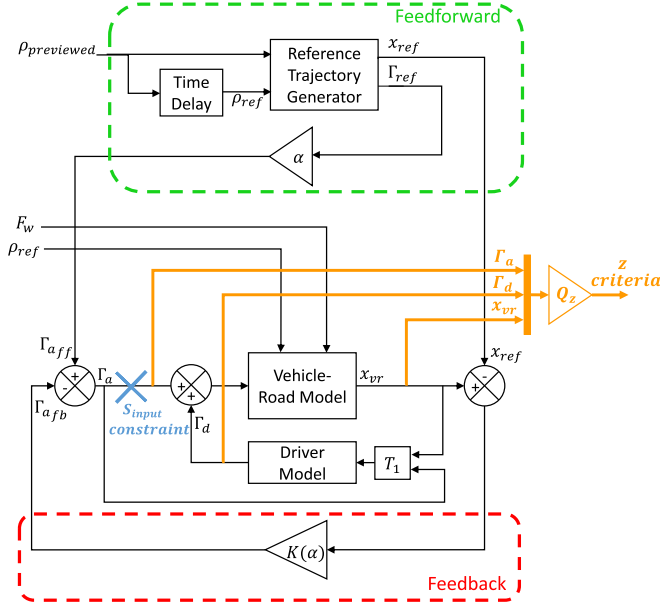


Fig. 2. Haptic shared control strategy.

driver model can be described as follows:

$$\begin{aligned} \dot{x}_d &= A_d x_d + B_d [\theta_{\text{far}} \quad \theta_{\text{near}} \quad \delta_d \quad \Gamma_s - \Gamma_a]^T \\ \Gamma_d &= C_d x_d \end{aligned} \quad (4)$$

where Γ_s is the self-aligning torque. The driver state vector x_d and matrices A_d , B_d , and C_d can be found in [25] or [26]. Driver model parameter values are given in Table II.

B. Haptic Shared Control Strategy

In HSC, both the driver and the assistance can apply a torque to the steering column. The driver applies a torque Γ_d through the steering wheel and the assistance applies a torque Γ_a through a motor on the steering column. The HSC synthesis aims at finding the assistance torque to be applied in order to fulfill some objectives. Here, the assistance torque must be calculated to conform to a certain sharing level α , which is the expected percentage of steering torque provided by the assistance system relative to the total torque applied to the steering wheel. Moreover, the assistance should allow for accurate lane-following and respect the driver's comfort. The proposed HSC strategy is divided into two sequentially designed parts: a "feedforward" part with an anticipatory action and a "feedback" part with a compensatory action. This control strategy is illustrated in Fig. 2. Block T1 represents the calculation of the inputs to

the driver model $[\theta_{\text{far}} \quad \theta_{\text{near}} \quad \delta_d \quad \Gamma_s - \Gamma_a]^T$. The feedforward part, which is shown in the green-dotted rectangle in Fig. 2, is composed of a trajectory generator. The latter has one input, the curvature of the road ahead of the vehicle [previewed at a time t , $\rho_{\text{previewed}}(t) = \rho_{\text{ref}}(t + T_{\text{horizon}})$, with $T_{\text{horizon}} = 2$ s], and the reference trajectory (Γ_{ref} control input, and state x_{ref}) as the output vector. These outputs are calculated by simulating an autonomous virtual vehicle based on the vehicle-road model (1), following the same road as the real vehicle. This virtual vehicle is driven by a H_2 -preview strategy that was developed in [27], a controller that provides accurate lane-following performance but does not take into account driver preferences. The feedback part is shown in the red-dotted rectangle in Fig. 2 and consists of a H_2/H_∞ regulator applied to the difference between the real road vehicle state x_{vr} and the virtual state x_{ref} as

$$\begin{aligned} \Gamma_{a_{\text{fb}}} &= K \cdot Y_{\text{diff}} \\ &= k_\beta \beta_{\text{diff}} + k_r r_{\text{diff}} + k_{\psi_L} \psi_{L_{\text{diff}}} + k_{y_L} y_{L_{\text{diff}}} \\ &\quad + k_{\delta_d} \delta_{d_{\text{diff}}} + k_{\dot{\delta}_d} \dot{\delta}_{d_{\text{diff}}} \end{aligned} \quad (5)$$

with $Y_{\text{diff}} = x_{\text{vr}} - x_{\text{ref}} = [\beta_{\text{diff}} \quad r_{\text{diff}} \quad \psi_{L_{\text{diff}}} \quad y_{L_{\text{diff}}} \quad \delta_{d_{\text{diff}}} \quad \dot{\delta}_{d_{\text{diff}}}]^T$.

Feedback gains $K = [k_\beta \quad k_r \quad k_{\psi_L} \quad k_{y_L} \quad k_{\delta_d} \quad k_{\dot{\delta}_d}]$ are calculated by solving the optimization problem (P) as

$$P : \begin{cases} \text{find } K \text{ such as:} \\ \min_K (\|T_{(\rho_{\text{previewed}}, F_w) \rightarrow z}\|_2) \\ \text{under constraints:} \\ \|S_{\text{input}}\|_\infty \leq S_{\text{max}} \end{cases} \quad (6)$$

where S_{input} is the system input sensitivity and z is the performance vector as

$$z = Q_z [\psi_L \quad y_{CG} \quad a_{\text{lat}} \quad (1 - \alpha)\Gamma_a - \alpha\Gamma_d \quad \Gamma_d \quad \Gamma_a]^T \quad (7)$$

where Q_z is a weighting matrix and y_{CG} is the lateral deviation at the vehicle center of gravity. The performance vector z is chosen to ensure precise lane-following performance, driver comfort, and good sharing performance.

Steering control sharing relies on the controller parameterization at two different places, as shown in Fig. 2. For the feedforward part, it allows to select part of the reference torque ($\Gamma_{a_{\text{ff}}} = \alpha\Gamma_{\text{ref}}$). For the feedback part, the sharing level is included during the synthesis process through the chosen criteria [see (7)]. As a result, it parameterizes all the feedback gains. This HSC strategy was tested on Simulink in MATLAB using a driver model to drive the vehicle [20]. The simulation was performed with a fixed sharing level α and the results showed accurate lane-following and few conflicts between the assistance system and the driver model.

C. Progressive Transition Using Haptic Shared Control

In order to use the HSC introduced in Section II-B, to make the transition between manual and autonomous driving, we need to be able to change the sharing level α while driving.

To resolve this point, feedback gains $K = [k_\beta \quad k_r \quad k_{\psi_L} \quad k_{y_L} \quad k_{\delta_d} \quad k_{\dot{\delta}_d}]$ [see (5)] were synthesized for different sharing levels ($\alpha = [0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9]$).



Fig. 3. Driving simulator (SCANeR-AVSimulation).

Feedback gains chosen for manual mode ($\alpha = 0$) were $K = [0 \ 0 \ 0 \ 0 \ 0 \ 0]$, as there is no assistance in this mode. For autonomous mode ($\alpha = 1$), the K vector was calculated using linear quadratic with integral action synthesis. The integral action relates to y_L and makes lane-following more accurate. Starting from the set of gain vectors thus calculated, we did a polynomial interpolation with tenth-order polynomials. Note that other interpolation approaches could accomplish the same tasks as the gains had a quasi-linear relationship between points. The resulting interpolation smoothly links the shared control solutions from purely manual to fully automated driving, and shows the absence of any overparameterization.

The level of sharing is a function of the selected transition profile and the location of the vehicle since the transitions were initialized at specific positions in the scenarios (see procedure).

III. EXPERIMENT

A. Participants

A total of 17 participants took part in the experiment (six women and 11 men), aged 24–53 years (mean = 30.94, SD = 8.20). They had at least three years of driving experience and travelled an average of 12 550 km per year (SD = 10 644 km). Each participant signed a consent form prior to the experiment. The study was reviewed and approved by the non-interventional research ethics committee of Nantes University (CERNI, IRB #IORG0011023, decision #08072021-2).

B. Equipment

This experiment was carried out using a fixed-base driving simulator (SCANeR Studio, AVSimulation) composed of a dashboard, a gear lever, three pedals (accelerator, brake, and clutch), an adjustable seat, a steering wheel, and a TRW steering system (see Fig. 3). The driver could see the visual environment on three LCD screens that cover a visual angle of 115° horizontally and 25° vertically. The vehicle model used corresponds to a Citroën C5. A motor was used to apply the assist torque to the steering column, which was equipped with a torque sensor. Specifically, the sensor measured the torsion of the column on



Fig. 4. Center screen of the simulator displaying the progressive bar while in autonomous mode.

a specific section between the steering wheel and the motor responsible for providing the torque feedback and the assistance torque. This information allowed to estimate the driver torque applied to the steering wheel with a small inaccuracy due to the residual friction. A human-machine interface (HMI) was used to communicate with the driver, consisting of a touch screen placed on the right-hand side of the steering wheel.

C. Procedure

Throughout the experiment, three different control modes were used: manual mode, shared control mode, and autonomous mode. In the manual mode, the only torque applied to the steering wheel is that of the driver. In the shared control mode, the torque applied to the steering wheel is the assistance torque added to the driver's torque. The contribution of the assistance torque depends on the sharing level. In the autonomous mode, the driver had to release the steering wheel and the only torque applied was the assistance torque. These modes only concerned the steering task, not the longitudinal control of the vehicle, as the vehicle speed was set using cruise control.

The steering mode was communicated to the participants in two ways. First, the HMI on the right-hand side of the steering wheel informed the participants about the driving mode. Second, a progress bar, shown in Fig. 4, was displayed at the bottom of the central screen superimposed on the visual scene. This progress bar represented the sharing level. In the autonomous mode, the bar was fully colored and the word “AUTO” appeared in its center. The participants were instructed to release the steering wheel and let the assistance drive autonomously only under this condition. The experiment was conducted in three steps, described in the following.

1) *Preliminary Phase*: The experiment began with a familiarization period. Participants were explained how to drive the simulator. The participants were instructed to accelerate until the vehicle reached the speed limit of 18 m/s. From that moment, they had to release the accelerator and the clutch pedal while continuing to control the steering wheel until the end of the simulation: that is, for about 10 min.

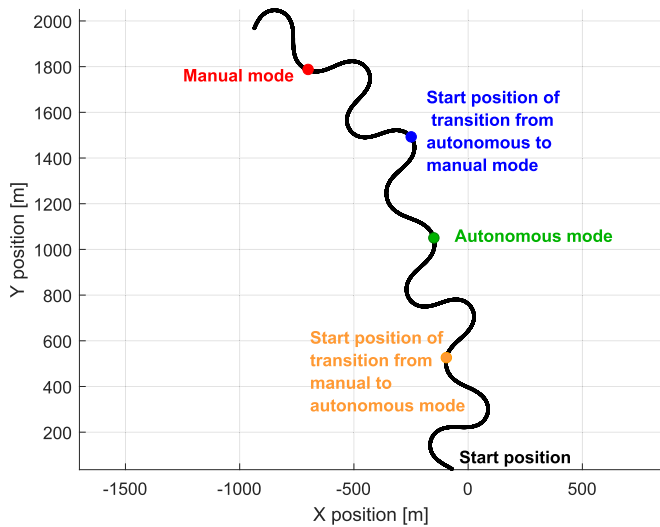


Fig. 5. Track for the first experimental phase.

2) *First Experimental Phase*: During the first phase of the experiment, the participants drove on a track composed of successive turns of 75 or 95-m radius of curvature (see Fig. 5). Before the simulation, the principle of shared control and the transition procedure were explained to the participants. Initially, the participants drove in manual mode. After a few meters, a sound and an indication on the HMI warned the participants that a transition from manual to autonomous mode was about to start. The transition lasted 50 s, and the participants were informed of the evolution of the sharing level by a progress bar. When the autonomous mode was reached, the participants had to release the steering wheel. After 590 m in autonomous mode, a new signal warned that a second transition was beginning, this time from autonomous to manual mode, again within 50 s. The purpose of this experimental phase was to allow the participants to become familiar with control transitions and allow them a considerable period of time to feel the progressiveness of the system. The phase also allowed validation of the control law by checking that the actual repartition between the driver and system corresponded to the desired repartition. To assess this distribution, an estimate of the instantaneous sharing level was used, which is calculated as follows:

$$\alpha_{\text{calculated}} = \frac{|\Gamma_a|}{|\Gamma_a| + |\Gamma_d|}. \quad (8)$$

3) *Second Experimental Phase*: The second phase of the experiment consisted of a test of four transition profiles in an obstacle-avoidance situation (see Fig. 8). The obstacle-avoidance situation occurred while the vehicle was in autonomous mode and the driver was involved in a secondary task. Then, as the assistance was not designed to avoid the obstacle, the driver had to regain control of the vehicle. Two scenarios were used with an obstacle placed either in a bend or a straight line. These scenarios will be referred to as the curve and straight-line scenarios, respectively. They are shown in Figs. 6 and 7.

Each scenario consisted of three parts. Participants first drove in manual mode for around 560 m for the curve scenario and

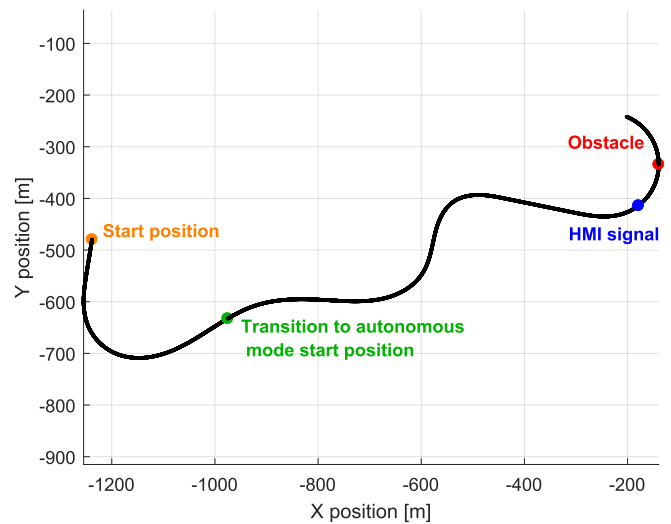


Fig. 6. Curve scenario track.

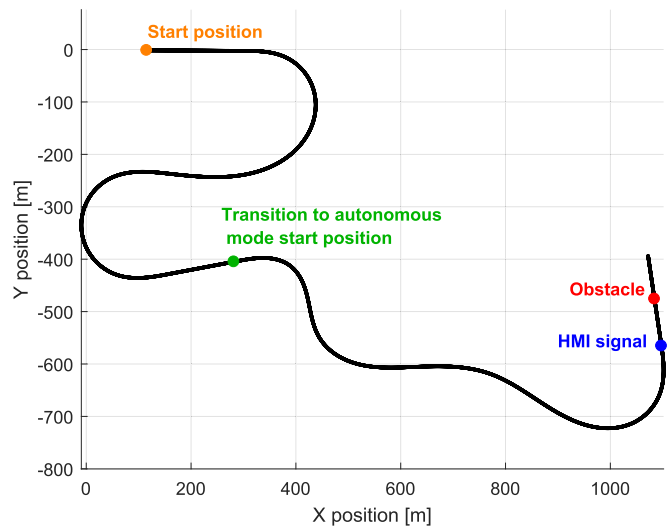


Fig. 7. Straight-line scenario track.



Fig. 8. Obstacle.

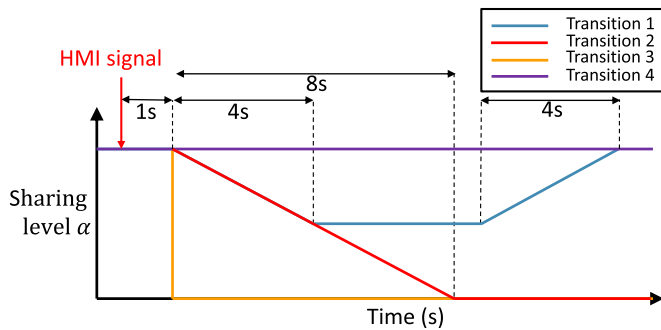


Fig. 9. Evolution of the sharing level for each transition profile.

1390 m for the straight-line scenario. Then, a gradual transition to autonomous driving mode was initiated. Once the autonomous mode was reached, the participants were asked to release the steering wheel and read aloud a text displayed on the HMI. To ensure that the participants were no longer monitoring the driving situation, they were instructed to avoid looking at the road while reading and to stop reading only if the HMI informed them that they should take control. After about 780 m of reading for the curve scenario and 920 m for the straight-line scenario, a takeover request was delivered. 1 s after the signal, one of the four transition profiles was activated, coinciding with the start of the obstacle-avoidance manoeuvre.

The evolution of the sharing level α during each of the tested transition profiles is shown in Fig. 9. These four transition profiles can be described as follows:

- 1) *Transition 1*: A progressive transition in 4 s from the autonomous mode to shared control mode ($\alpha = 0.5$); then, once the obstacle was passed, another transition of 4 s from the shared control mode to autonomous mode.
- 2) *Transition 2*: A progressive transition of 8 s from the autonomous to manual mode.
- 3) *Transition 3*: A binary transition from the autonomous to manual mode.
- 4) *Transition 4*: The vehicle remains in the autonomous mode, but the assistance torque was limited to 5 N · m. The driver keeps the ability to override the system's action.

Each participant experienced the four transition profiles in a randomized order and each transition profile was verbally explained to the participants before the trials. For each transition profile, the participant had to drive three times, once with the transition in a bend (see Fig. 6), a second time in a straight line (see Fig. 7), and finally in a bend again (same condition as the first drive). The objective of repeating the curve scenario was to assess whether the performance during transitions changed depending on whether the driver was surprised by (first try) or habituated (third try) to the takeover.

After each condition, the participants had to answer four questions on Likert scales.

- 1) *Question 1*: Did you feel that the transition was smooth (gradual and seamless)?
- 2) *Question 2*: Did you feel that the assistance system helped you?
- 3) *Question 3*: What was the level of intrusiveness of the system?

- 4) *Question 4*: Did you get the impression that the system guaranteed your safety?

D. Dependent Variables

Objective indicators were used to assess the transition profiles.

- 1) The steering wheel reversal rate, SWRR, which provides information on the stability of the steering control.
- 2) The maximum absolute lateral deviation $\max(|y_L|)$.
- 3) The mean absolute driver torque $\text{mean}(|\Gamma_d|)$.
- 4) The metric W in (9)–(12) represents the physical workload related to the driver's steering activities. From the viewpoint of energy consumption, this metric can be interpreted as the steering energy provided by the driver within a duration T to perform a desirable steering maneuver [28], [29]. If the value of W is positive, it is motor work and if negative, it is resistant work. The positive and negative steering workload, W_+ and W_- are, respectively, defined as

$$W_+ = \int w_+(t) dt \quad (9)$$

$$W_- = \int w_-(t) dt \quad (10)$$

with

$$w_+(t) = \begin{cases} \Gamma_d(t)\dot{\delta}_d(t) & \text{if } \Gamma_d(t)\dot{\delta}_d(t) \geq 0 \\ 0 & \text{else} \end{cases} \quad (11)$$

$$w_-(t) = \begin{cases} -\Gamma_d(t)\dot{\delta}_d(t) & \text{if } \Gamma_d(t)\dot{\delta}_d(t) < 0 \\ 0 & \text{else.} \end{cases} \quad (12)$$

We used this objective index to evaluate the driver's comfort from the viewpoint of the driver's interaction with the assistance controller via the steering wheel. Such objective analysis using steering workload has been widely used directly or indirectly for driver comfort analysis in many steering assistance or shared control works [30], [31].

In addition, the scores measured on the four Likert scales at the end of the experiment (see Section III-C3) provided four subjective indicators.

A repeated-measures ANOVA was carried out on each of these indicators in order to decide whether the transition profile had a significant effect. Tukey HSD tests were performed for posthoc comparisons. The results for the straight-line scenario were tested using one-way ANOVA with profile as the only independent variable. For curve scenarios, two-way ANOVAs were used with trial repetition as a second variable.

IV. RESULTS

A. Preliminary Validation of the Shared Control Strategy

The analysis of the first phase of the experiment allows validation of the control strategy chosen for the transition between manual and autonomous driving. Fig. 10 shows that as the required sharing level α increases, the assistance torque also increases, as expected. This allows the participants to gradually release the steering wheel, resulting in a progressive decrease in driving torque. In addition, the lateral deviation curve shows

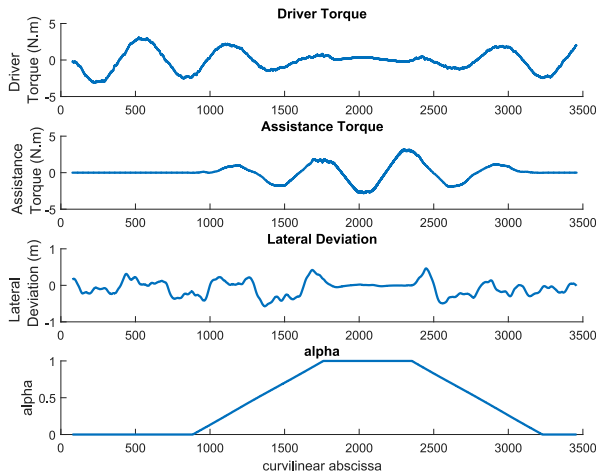


Fig. 10. Driver torque, assistance torque, and lateral deviation averaged across the participants as a function of the curvilinear abscissa of the road during the first phase of the experiment. The evolution of the sharing level is shown in the bottom graph.

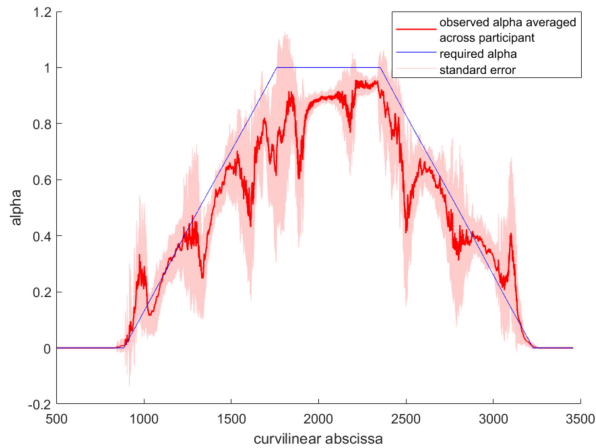


Fig. 11. Actual sharing level during the simulation averaged across the participants compared with the required sharing level.

that lane tracking was very accurate when the vehicle was in autonomous mode since the lateral deviation was close to 0. Fig. 11 shows the comparison of the required sharing level and the actual sharing level, varying over time, during the simulation. Note that the actual sharing level follows, on average, the requested level. The reason why the actual sharing level is not equal to 1 when in autonomous mode is that there is always a residual torque due to the friction in the steering system that is measured by the sensor even if the driver releases the steering wheel.

In conclusion, this first test shows that the progressive transition strategy gives the expected results. Participants decreased their contribution to steering torque when α increased and gradually regained steering control when α decreased.

B. Transition Profiles Comparison

1) *Objective Indicators:* The second phase of the experiment aimed to compare the four transition profiles described in Section III-C3. ANOVAs were calculated for the two curve trials on the one hand and for the straight-line trial on the other hand.

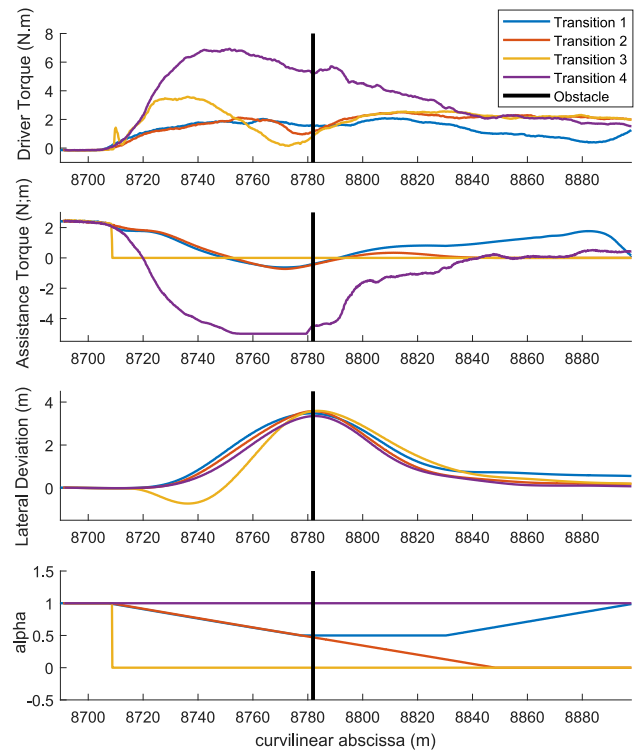


Fig. 12. Driver torque, assistance torque, and lateral deviation averaged across the participants as a function of the road curvilinear abscissa in the curve scenario. The sharing level is shown in the bottom graph.

Fig. 14 shows that the average driver torque was significantly influenced by the transition profile [$F(3, 48) = 73.4, p < 0.001$ for the curved scenario and $F(3, 48) = 332.1, p < 0.001$ for the straight-line scenario]. The effect in the straight-line scenario resides in a higher average torque for Transition 4 than for the others ($p < 0.001$ in all cases). In the curved scenario, the different profiles are more distinct. Transition 1 resulted in a lower average driver torque than for the other transitions ($p < 0.05$ compared to Transition 2; $p < 0.001$ compared to Transitions 3 and 4). On the other hand, the driver torque observed with Transition 4 was higher than for the other transitions ($p < 0.001$). Further, it can be seen in Fig. 12 that the driver torque is almost identical before the obstacle for transitions 1 and 2 but is lower in the case of Transition 1 after the obstacle. This is consistent with the evolution of the sharing level: for Transition 1, the assistance continued to deliver a large part of the steering torque needed to take the turn, whereas for Transition 2, the participants had to deliver that torque and return to the initial lane after avoiding the obstacle. To see in more detail how these torques evolved, we can observe the positive and negative driver workload.

Fig. 14 also shows that the transition profiles had a significant effect on the positive steering workload [$F(3,48) = 15.5, p < 0.001$ for the curve scenarios and $F(3,48) = 23.6, p < 0.001$ for the straight-line scenario] and negative steering workload [$F(3,48) = 42.0, p < 0.001$ for the curve scenarios and $F(3,48) = 31.9, p < 0.001$ for the straight-line scenario]. Multiple comparison tests show that the negative steering workload was larger for Transition 4 than for other transition profiles for all scenarios ($p < 0.001$), which indicates that the participants

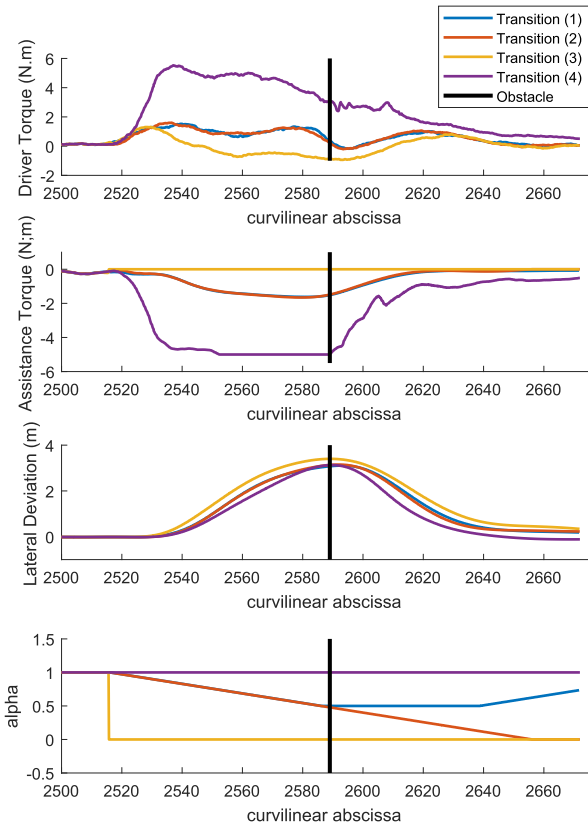


Fig. 13. Driver torque, assistance torque, and lateral deviation averaged across the participants as a function of the road curvilinear abscissa in the straight-line scenario. The sharing level is shown in the bottom graph.

resisted the assistance more during Transition 4 than in other transition profiles. For the positive driver workload, there is a difference between the curve and straight-line scenarios. For curve scenarios, the positive driver workload is larger for Transitions 3 and 4 than for Transitions 1 and 2 ($p \leq 0.01$), whereas for the straight-line scenario, the positive driver workload is only larger for Transition 4 ($p < 0.001$). These results show that in both scenarios the driver had to provide more torque for Transition 4 than for the other profiles. In the curve scenario only, the driver also had to provide more torque for Transition 3 than for Transitions 1 and 2, as there was no assistance during the curve.

The transition profile had a significant effect on the SWRR [$F(3,48) = 8.7, p < 0.001$ for the curve scenarios and $F(3,48) = 9.3, p < 0.001$ for a straight-line scenario; see Fig. 14]. For the curve scenario, multiple comparison tests show that SWRR was higher for Transition 3 than for Transitions 1 and 2 ($p \leq 0.001$ for Transition 3 compared with Transitions 1 and 2). It was also higher for Transition 4 than for Transition 1 ($p = 0.03$). For the straight-line scenario, these tests show that SWRR was higher in the case of Transition 4 than in other transition cases ($p \leq 0.001$ when compared with other profiles).

Another significant effect of the transition profile was found on the maximum lateral deviation [$F(3,48) = 3.1, p = 0.036$ for the curve scenarios and $F(3,48) = 5.1, p = 0.004$ for the straight-line scenario; see Fig. 15]. For the curve scenario, posthoc tests revealed that the maximum lateral deviation was

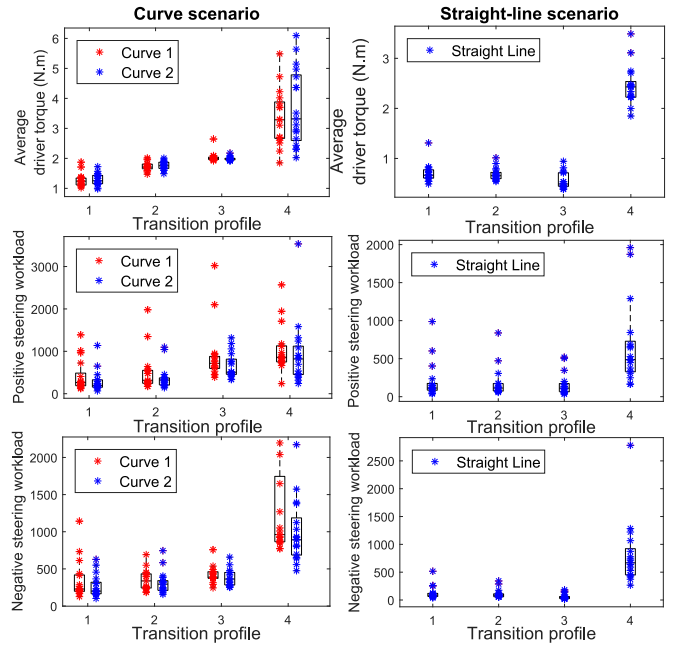


Fig. 14. Positive and negative steering workload, and average driver torque in the curve scenarios on the left and in the straight-line scenario on the right.

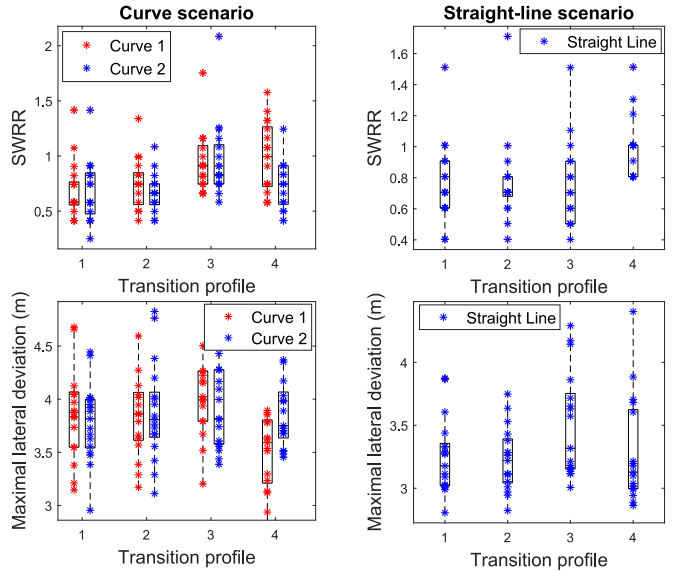


Fig. 15. SWRR and maximum lateral deviation in the curve scenarios on the left and in the straight-line scenario on the right.

larger in Transition 3 than in Transition 4 ($p = 0.02$). In the straight-line scenario, the maximum lateral deviation was larger in Transition 3 than in all other cases ($p < 0.05$). Thus, when no assistance torque was present, the drivers made a slightly larger lateral deviation to avoid the obstacle. However, the avoidance paths remained relatively close in all conditions, especially in the straight line (see Fig. 13). In the bend, an initial deviation in the opposite direction due to the absence of assistance was observed for Transition 3. This is shown in Fig. 12, where the average lateral deviation curve shows negative values for some time at the beginning of the maneuver. This is due to the sudden removal of the assistance torque after the takeover request. As

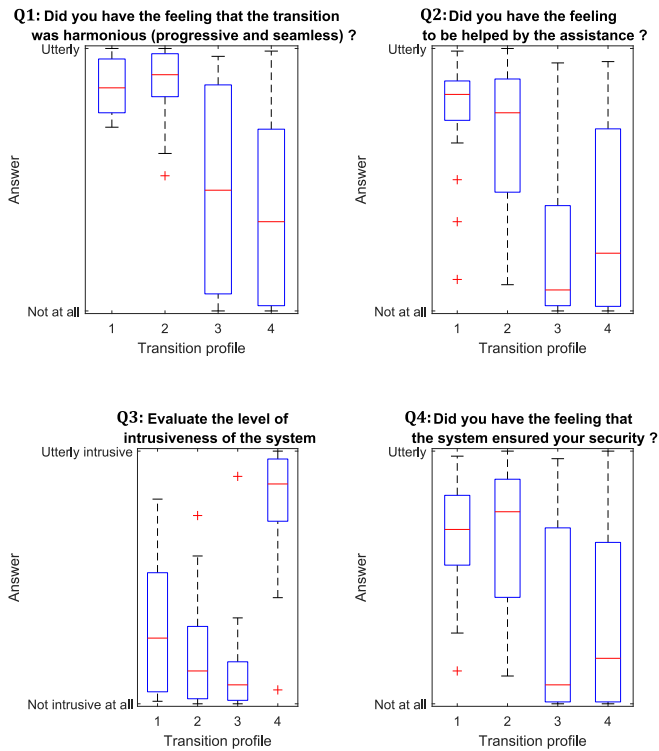


Fig. 16. Answers to questions on a Likert scale from 0 to 10.

participants were in a curve when it happened, the vehicle moved toward the outer-edge line of the road, and participants then had to swerve back toward the lane center and beyond to avoid the obstacle. This explains the spike at the beginning of the driver torque curve in Fig. 12.

Finally, there was no significant effect of the repetition of the curve scenario for the maximum absolute lateral deviation and the mean absolute driver torque [we obtained $F(1,16) = 0.6$, $p = 0.47$ and $F(1,16) = 1.9$, $p = 0.18$, respectively]. However, repetition had a significant effect on the positive and negative steering workload [$F(1,16) = 24.0$, $p < 0.001$ and $F(1,16) = 13.4$, $p = 0.002$]. Posthoc tests show that there is a significant reduction of the negative steering workload for Transition 4 between the first and the second curve trials, which indicates that the driver resisted the action of the system to a lesser extent. For the positive steering workload, there was no significant posthoc difference. The repetition of the curve scenario also had a significant effect on the SWRR [$F(1,16) = 6.3$, $p = 0.02$]. According to multiple comparison tests, SWRR was higher for the first curve trial than for the second one in the case of Transition 4 ($p = 0.009$).

2) *Subjective Indicators:* Responses to the four questions posed to the participants after experiencing each transition profile were analyzed. Fig. 16 shows that the transition profile had a significant effect on these data [$F(3,48) = 15,7$, $p < 0.001$ for the first question; $F(3,48) = 13,2$, $p < 0.001$ for the second question; $F(3,48) = 33,3$, $p < 0.001$ for the third question; and $F(3,48) = 7,3$, $p < 0.001$ for the last question]. Transitions 3 and 4 were significantly different from Transitions 1 and 2 for Questions 1, 2, and 4 ($p < 0.01$ in all cases). For these three questions, Transitions 3 and 4 were not significantly different from each other, and nor were Transitions 1 and 2. This means

that the participants found Transitions 3 and 4 to be less smooth, less useful, and less safe than Transitions 1 and 2. For Question 3, Transition 4 was significantly different from all other transitions ($p < 0.001$). Participants therefore found Transition 4 more intrusive compared to the others, which is consistent with the objective steering workload indicator in Fig. 14.

C. Discussion

The objective of this study was to validate the relevance of the HSC strategy developed in [20] to achieve transitions between autonomous and manual control. This was done first by analyzing the effective sharing of control between the driver and automation during a long transition and then by comparing different transition profiles during obstacle avoidance in straight lines and curves. In the first experimental phase, we observed the ability of the system to perform transitions when the driver and the assistant had compatible reference trajectories at all times. On the other hand, in the second experimental phase, the driver deviated from the reference trajectory of the assistance and it was necessary to quickly give back the control of the steering wheel.

The first phase of the study showed that the actual level of sharing during the simulation followed the requested level of sharing. Drivers gradually gave way to the assistance system as the level of sharing increased. They also gradually increased their steering activity when they returned to manual control. The second phase confirms these results, as it has been shown that smooth transitions (Transitions 1 and 2) are more effective in terms of both steering performance and subjective feeling than a binary transition to manual control (Transition 3) or having to override the autonomous mode (Transition 4). This was particularly true when the transition occurred during a turn. These results support the idea that the HSC strategy proposed in [20] is a valid candidate to facilitate transitions between the manual and autonomous modes.

In the straight-line scenario, the benefit of using a gradual transition instead of a binary transition has not been demonstrated. Indeed, the results obtained for Transitions 1, 2, and 3 were very similar. This can be explained by the fact that the action of the autonomous mode before the transition kept the vehicle well aligned on the road axis. As a result, the driver recovered manual control under ideal conditions, without the need to be assisted in their actions. In contrast, it is important to note that the driver was not hindered by the assistance system during the gradual transition even though the system continued to tend to keep the vehicle in the lane. The advantage of using a gradual transition using the HSC only becomes apparent when compared to Transition 4, for which the driver had to override the action of the autonomous system. In this case, the assistance torque was significantly higher during obstacle avoidance. Although the system torque was easily overcome, the system resistance induced a higher driver torque, which adversely affected the driver's subjective assessment of the system.

In the curve scenarios, the advantage of using gradual transitions was more obvious. First of all, at the beginning of the transition, Transitions 1 and 2 provided an assisting torque that helped the driver stay on the right trajectory to follow the road

while allowing the driver the freedom to deviate from it. On the contrary, in the case of a binary transition, the vehicle's trajectory was no longer supported and the driver had to correct the induced deviation. In addition, Transition 1 allows the driver's torque to be further reduced by helping the driver to return to the lane center after obstacle avoidance. For Transition 4, the driver received lane-tracking assistance throughout the entire maneuver, but the torque required to override the assistance and avoid the obstacle was too high to make this system acceptable to drivers.

V. CONCLUSION

This article described a strategy to achieve transitions between manual and autonomous driving modes. This strategy is based on an HSC system that was adapted to be able to gradually modify the sharing level during the transition phase. This was then tested with real drivers on a driving simulator. The results demonstrated first that the transition strategy gives the expected results as the driver's torque corresponded to the sharing level. Second, when different transition profiles were compared, gradual transitions produced the best steering performance and the most favorable subjective evaluation.

To confirm these results, this transition strategy needs to be tested under a wider range of conditions and in a real vehicle. For example, consideration can be given to road conditions. Indeed, on icy or wet roads, some drivers will want to have full control of the car, while others will not have confidence in their own abilities and will rely much more on the system. The question of the temporality of transitions is also a central issue to be addressed, as it may depend on the use case considered and the preferences of the driver. Finally, it would be wise to compare the performance of this HSC strategy with others proposed in the literature.

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