Transition Management Between an Autonomous Vehicle and a Real Human Driver, in a Context of Take-Over Request

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Abstract: This paper presents a new shared lateral control approach to deal with the transition management between the human driver and the autonomous system. The objective of this shared control is to realize a smooth and safe switching between the two agents steering inputs during a lane keeping maneuver. The different driving modes including the transition system are detailed. Two transition modes are defined. The human driver acts on the vehicle's lateral control. The autonomous system consists of longitudinal and lateral controller developed based on Super Twisting Sliding Mode (STSM) control approach. Then, the control authority allocation is performed using the mixing shared control that permits the fusion of two inputs via a fusion parameter. To do that, a coordinator based on a decision algorithm is developed for the driving modes and the fusion parameter determination. Finally, validation of the proposed shared control is done on the "*SCANeR Studio*" (OKtal) professional simulator with the human in-the-loop through the "*Logitech G29*" steering wheel for two different scenarios.

Keywords: Human-machine cooperative control, transition system, cooperative driving, shared lateral control, decision-making, autonomous driving.

1. INTRODUCTION

According to National Highway Traffic Safety Administration (NHTSA) statistics, human leads to 90% of road accidents [Rajamani (2012)]. In such situation, when the driver is tired or distracted, he can be assisted by an Advanced Driving Assistance System (ADAS) to prevent a critical situation. These systems reduce traffic accidents and facilitate the driver's task. This new technology of automated system starts to emerge progressively in order to automate the driving activities. There are 6 levels of automation: from 0 to 5 [Favarò et al. (2017)]. The challenge now is to realize a full autonomous vehicle (level 5) where the driver is eliminated from the control loop. However, replacing the traditional vehicles by the autonomous one needs more time to be reached. The realization of full autonomous vehicles should be evaluated step by step considering many criteria: system's robustness, road safety, ethics rules and the high cost of hardware and software, etc. On the other hand, there are many levels of autonomy where the presence of human driver is essential to navigate safely on the road (SAE level 3 and 4). In level 3, the human is the main responsible of driving tasks. He supervises the scene, monitors the vehicle's control and reacts if the automated system reaches his limits for many reasons: sensor's failures, lack of localization information, bad weather, etc. However, in the higher level of automation (level 4), the system accomplishes all driving tasks without driver's intervention. The driver can retain the control action if he is available. In addition, even if the driver is trusted during autonomous mode (auto mode), a smooth transition from auto to manual mode is needed to ensure this switching. Moreover, according to the NHTSA [Ayoub et al. (2019)], the autonomous system should inform the driver about its status: (1) normal/abnormal functioning, (2) Available/not available for autonomous driving mode and (3) On/Off transition request from automated system to the driver. Thus, the transition between the manual driving and autonomous driving modes creates a new challenge for the automotive industry and researches. This transition can be from autonomous to manual driving mode and vice-versa.

On the other hand, the shared control is a new aspect of control in the automotive field that ensures road's safety and enhances driving performance. During this collaborative control, the human and the autonomous controller cooperate together to accomplish a common goal simultaneously. In this work, we will treat the shared lateral control in order to realize a safe and smooth transition when switching between both agents. This transition is defined as shared control where the driver and the autonomous system are in charge of driving tasks. Many advanced studies have been developed in the literature to investigate the shared control between driver and an automated system. In Rath et al. (2018), a shared control approach was developed based on nonlinear vehicle-road-driver model for the lane keeping purpose. A sharing parameter was integrated in the shared design to consider the conflict between the two agents. There are two types of shared control: the blending shared control and the haptic shared control. The authors in Johns et al. (2016) proposed a haptic-feedback shared control between the driver and the automated system using the torque on the steering wheel. The study shows that the haptic feedback torque on steering wheel is insufficient to predict the driver's intention in the future. A two-phase haptic interface based on the human-machine interaction is developed in Lv et al. (2021) to manage the authority shift from autonomous to manual mode. This haptic torque on the steering wheel aims to guide and assist the human while he is engaged in the control loop, depending

on his ability. However, the shared control can cause a conflict in dangerous situations. A haptic guidance torque calculated with respect to the driver's behavior is presented in Boink et al. (2014) to mitigate the conflict between both agents. Other studies represent the shared control as transition control phase affected by the human's factors. In Kim et al. (2018), the authors presented a driver's cognitive model to analyze the influence of driver's experience and workload on the transition between the two agents. The authors in de Winter and Dodou (2011) have explored the topic of shared control in terms of its advantages and drawbacks on the driving tasks. They presented the risks that can occur during this shared control, the conflict for example, and the influence of this control strategy on the driver's skills. A planned control transition was applied in Holländer and Pfleging (2018) to switch from automated system to the driver by using the auditory and visual information systems. These systems help and prepare the human who is engaged in non driving related activities to be ready for regaining control. Moreover, an overview for the last ten years was done in Ayoub et al. (2019), and summarizes the different works related to the shifting from manual to autonomous driving.

All these interesting research have motivated us to develop a shared lateral control to address the transition management between the human and the automated system. The shared lateral control is done for the lane keeping purpose using steer-by-wire system. However, this method can be adapted to consider the tracking of a local trajectory with more complex maneuvers (overtaking, collision avoidance...). Thus, in our present work, a new shared lateral control is developed to manage the transition control in order to ensure a smooth switching and enhance road safety. Our contribution is illustrated in the development of a transition system. Two modes are defined in the transition system, that ensure the shifting from auto to manual mode and vice-versa, according to many criteria: the Driver's availability (DA), the conflict on the driver's behaviors ($\delta_{conflict}$), and the take over request (TOR). Then, a coordinator based on a decision algorithm is developed for the determination of the driving mode. Finally, two scenarios are considered to test and validate the proposed shared lateral control on "*SCANeR Studio*" (OKtal) professional simulator. Validation is done to show the effectiveness of this method in terms of driving performance enhancing and vehicle's stability keeping.

The rest of the paper is as follows: in Section 2, the different driving modes including the transition system are given. Then, the proposed shared lateral control is detailed in Section 3. A coordinator based on a decision algorithm is introduced, then the shared lateral control authority is detailed to blend the two inputs. In Section 4, system's validation is done by describing the simulations tools and presenting the simulations results of two detailed scenarios. The validation of the proposed shared control is done with a complete nonlinear model on "*SCANeR Studio*" (OKtal) simulator interacted with human through the "*Logitech G29*" steering wheel. Finally, the conclusions and the perspectives for future work are given in Section 5.

2. DRIVING MODES

Fig.1 shows the global shared lateral control architecture. It is composed of two parts: the Driving modes and the shared lateral control. The different driving modes are detailed in the following.

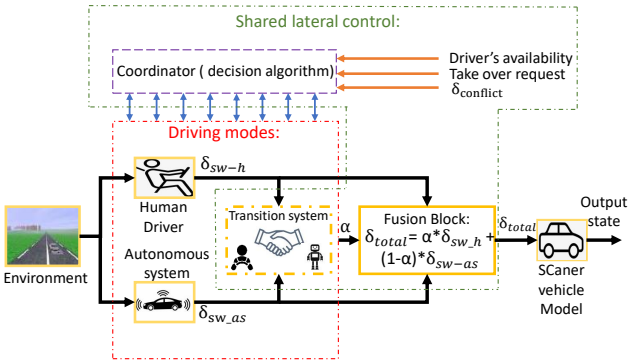

Fig. 1. Architecture of the shared lateral control.

2.1 Human Driver

A real human driver acts on the vehicle's lateral control through a steering wheel (human in-the-loop). His steering input will be noted as δ_{sw-h} in this paper.

2.2 Autonomous System

A robust autonomous system based on the super-twisting sliding mode (STSM) algorithm is developed to realize a lane keeping maneuver at the desired velocity. The autonomous system consists of longitudinal and lateral robust controllers. The autonomous controller is validated separately on Matlab/Simulink using the robotic formalism of nonlinear vehicle model validated on "*SCANeR Studio*"simulator. Let us introduce briefly the STSM theory. The main idea is to define a sliding surface, representing the desired behavior of the system, where the dynamic states are forced to reach this surface during a finite time and remain on it. Consider the second order system given as:

$$\dot{X} = f(X,t) + g(X,t)u(t) \tag{1}$$

where $X = [x, \dot{x}]^T \in \Re^2$ is the state vector, u is the control input, and f, g are continuous functions. X^* is the desired state of X with $X^* = [x^*, \dot{x}^*]^T \in \Re^2$. The error vector is given by $E = X - X^* = [e, \dot{e}]^T \in \Re^2$ where $e = x - x^*$ and $\dot{e} = \dot{x} - \dot{x}^*$. Therefore, a sliding variable s with relative degree $r = 1$ w.r.t the control input, is defined as:

$$s = \dot{e} + k\, e. \tag{2}$$

The second order derivative of s can be expressed as:

$$\ddot{s}(s,t) = \Phi(s,t) + \xi(s,t)\dot{u}(t) \tag{3}$$

where $\Phi(s,t)$ and $\xi(s,t)$ are unknown bounded functions.

The goal of the Super-Twisting algorithm is to force the sliding variable s to converge to zero ($s = 0$) in finite time. Assume that there exist positive constants S_0, b_{min}, b_{max}, C_0, U_{max} verifying for all $X \in \Re^n$ and $|s(X,t)| < S_0$:

$$\begin{cases} |u(t)| \leq U_{max} \\ |\Phi(s,t)| < C_0 \\ 0 < b_{min} \leq |\xi(s,t)| \leq b_{max} \end{cases} \tag{4}$$

Thus, the control input based on the Super-Twisting Sliding Mode algorithm [Rivera et al. (2011)] is given as:

$$u(t) = u_1 + u_2 \begin{cases} u_1 = -\alpha_1 |s|^{\tau} \text{sign}(s), \;\; \tau \in]0,\, 0.5] \\ \dot{u}_2 = -\alpha_2 \text{sign}(s) \end{cases} \tag{5}$$

α_1 and α_2 are positive gains. The following conditions guarantee the finite time convergence:

$$\begin{cases} \alpha_1 \geq \sqrt{\frac{4C_0(b_{max}\alpha_2+C_0)}{b_{min}^2(b_{min}\alpha_2-C_0)}} \\ \alpha_2 > \frac{C_0}{b_{min}} \end{cases} \quad (6)$$

The convergence analysis is shown in Utkin (2013).
The controller synthesis is based on a robotic formalism model presented in Chebly et al. (2019), Chebly (2017) (more details in Appendix A), that represents the coupling between the longitudinal and lateral dynamics. Based on this model, we choose the two sliding variables for the longitudinal and lateral controllers as follows:

$$\begin{aligned} s_1 &= e_{Vx} + \lambda_x \int e_{Vx},\ \lambda_x > 0 \\ s_2 &= \dot{e_y} + \lambda_y e_y, \qquad \lambda_y > 0 \end{aligned} \quad (7)$$

where λ_x and λ_y are positive constants, and, e_{Vx} (e_{Vx}= V_x-V_x^*) and e_y (e_y= y-y^*) are the vehicle longitudinal speed error and the lateral error respectively. The sliding variables s_1 and s_2 have a relative degree equal to one w.r.t the inputs respectively, the driving/braking torque Γ_c for the longitudinal dynamics and the steering wheel angle δ_{sw-as} for the lateral dynamics. Thus, in order to converge these variables to zero and the controlled states follow the desired ones, and based on the above discussion, the torque and the steering angle control applied to the vehicle, are given by:

$$\begin{aligned} &\Gamma_c = -\alpha_{\Gamma_c,1}|s_1|^{\tau_{\Gamma_c}} sign(s_1) - \alpha_{\Gamma_c,2}\int_0^t sign(s_1)d\tau, \\ &\delta_{sw-as} = u_1 + u_2 + \delta^* \quad \begin{cases} u_1 = -\alpha_{\delta,1}|s_2|^{\tau_\delta} sign(s_2), \\ u_2 = -\alpha_{\delta,2}\int_0^t sign(s_2)d\tau, \\ \delta^* \text{ is the equivalent control input,} \end{cases} \end{aligned} \quad (8)$$

where $\alpha_{\delta,i}$ and $\alpha_{\Gamma_c,i}$ with i = [1, 2], are positive constants satisfying the conditions in (6). τ_{Γ_c} and τ_δ are constants in]0, 0.5]. The controller gains are given in Chebly et al. (2019). Finally, δ^* is the equivalent control input, corresponding to the steering wheels angle at the equilibrium when $\dot{s_2} = 0$.

2.3 Transition System

The transition system is defined in the way to switch from the auto to manual mode or from manual to auto mode. For that, two modes are defined to realize these transitions. The transition structure is given in the Fig.2(a). The two modes are given as:

- Transition mode 1: This mode is defined to switch from the auto mode to the manual mode after a take over request demanded by the driver (Fig.2(b)). We define α_{des} function of the driver's availability (DA) and the conflict on the driver's behaviors ($\delta_{conflict}$). The role of α_{des} is to determine the direction of transition (from auto to manual mode or vice-versa, auto mode corresponds to 0, and manual mode corresponds to 1), depending on the driver's availability and behaviors. α_{des} is the desired reference for the fusion parameter α, given as:

$$\alpha_{des} = DA * (1 - \delta_{conflict}) \quad (9)$$

This transition is done, if the driver demand a take over request ($TOR = 1$) and $\alpha_{des} = 1$, that means the driver is available to take the action of vehicle's control ($DA = 1$), and there is no conflict on his behavior ($\delta_{conflict} = 0$). So, the transition mode 1 is activated in order to switch to the manual mode and α increases from 0 to 1 in $T_{up} = 1.5s$. α is the fusion parameter varying between 0 and 1 to blend the two agents steering inputs. α is equal to 0 in auto mode and to 1 in manual mode. The driver's availability (DA) is a dynamic variable related to the driver, and can be calculated based on different factors: driver's eyes movement, driver's head position, level of driver's sleepiness, etc. Therefore, the calculation of diver's availability is not in the scope of this work and it is considered as an input to the transition system. On the other hand, $\delta_{conflict}$ is the difference between the steering wheel angle applied by the driver (δ_{sw-h}) and the approximate steering angle (δ_{approx}) on the desired trajectory given as:

$$\delta_{conflict} = B_{\delta_{threshold}}(|\delta_{approx} - \delta_{sw-h}|) \quad (10)$$

$$\delta_{approx} = \rho^* * (l_f + l_r) \quad (11)$$

with ρ^* the curvature of the desired trajectory, l_f and l_r the distances from the center of the vehicle to the front and rear wheels respectively. The conflict of the driver's behavior, $\delta_{conflict}$ is a Boolean value, equal to 0 or 1 depending on $\delta_{threshold}$ a threshold from which we consider that there is a conflict on the driver's behavior.
- Transition mode 2: The aim of this mode is to assure the transition from the manual mode to the auto mode, in the case when the human driver is totally engaged in the driving tasks (manual mode) and suddenly the value of α_{des} is equal to 0 (Fig.2(b)). So, the transition mode 2 is activated to realize the transition from manual mode to auto mode and α decreases from 1 to 0 in $T_{down} = 0.2s$. In this case, the transition mode 2 is an example of Advanced driving Assistance system (ADAS) application. In addition, the transition mode 2 is activated if during the transition from auto to manual mode (transition mode 1), suddenly the value of α_{des} is equal to 0, that means if a conflict occurs on the driver's behaviors, or the driver is not available during this phase (Fig.2(b)). Thus, the transition to the auto mode is done and α decreases from α_0 ($\alpha_0 < 1$) to 0, respecting the same decrease speed.

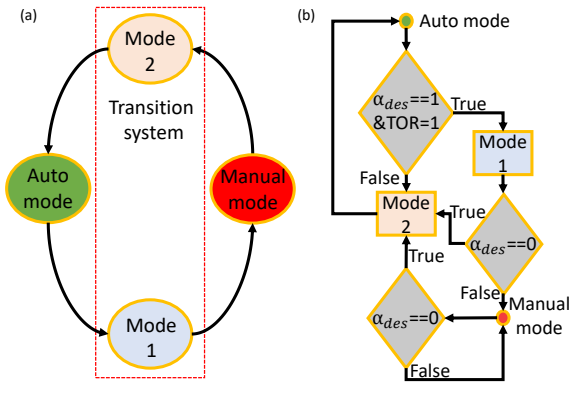

Fig. 2. The structure of the transition system

3. SHARED LATERAL CONTROL ARCHITECTURE

This section details the proposed shared lateral control (see Fig.1). A coordinator based on a decision algorithm is developed to determine the way of switching between the different driving modes. Then the control authority between the two agents is presented.

3.1 Coordinator

In order to determine the driving mode and the value of the fusion parameter, a coordinator is needed to switch between the different driving modes: Auto mode, manual mode and finally the modes 1 and 2 of the transition system (see Fig.3). These modes are defined as:

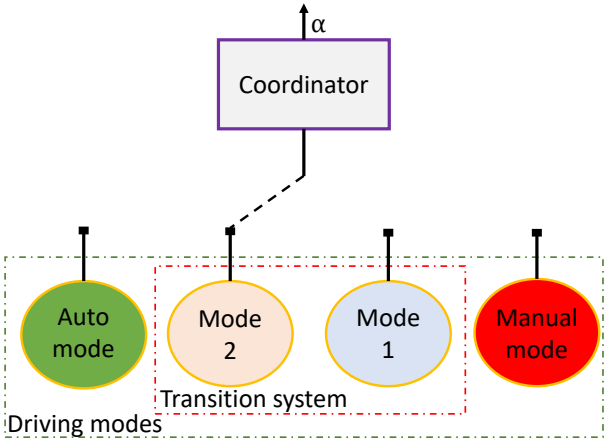

Fig. 3. The structure of the coordinator

- Auto mode: an autonomous controller provides the vehicle with the appropriate torque for the longitudinal movement. For the lateral dynamics, a robust controller generates the steering angles to follow the desired trajectory and keep the lane. Noting that, in this mode the steering wheel and the wheels are decoupled corresponding to a steer-by-wire system.
- Manual mode: The human driver acts on the vehicle's lateral control by using the steering wheel, "*Logitech G29*" (Fig.6(a)), while the longitudinal controller is realized by the autonomous controller. The driver can demand a take over action by pressing the bottom *R*2 and he can turn off the manual driving by using the bottom *L*2 (see Fig.6(b)).
- Transition system's modes: transition mode 1 and 2 are detailed above to describe the switch from Auto mode to the Manual mode and vice-versa.

Then, a decision algorithm (given below) is developed in this layer for the switching between the different modes, and the determination of the final value of fusion parameter α.

3.2 Shared Lateral Control Authority

The shared control authority allocation between the driver and the autonomous system is performed by using the blended shared control [Borroni and Tanelli (2018)] which allows the fusion of two inputs from each agent. This form of shared control is used in the steer-by-wire system, where there is no mechanical link between the two inputs. The familiar form of blending shared control is the mixing using weight parameter (see. [Li et al. (2020)], [Li et al. (2018)]). The total blending control input is given as:

$$\delta_{total} = \alpha * \delta_{sw-h} + (1-\alpha) * \delta_{sw-as}, \qquad (12)$$

where δ_{total}, δ_{sw-h} and δ_{sw-as} are the total steering wheel angle, steering wheel angles of human driver and autonomous system respectively. α is the fusion parameter representing the influence proportion of each agent on the total steering angle. α is bounded in [0,1], calculated depending on the decision algorithm in the coordinator.

Algorithm 1 A decision algorithm for the switching purpose

```
if (Take over request equal to 0 (TOR=0)) then
    Auto mode is activated (α = 0)
else
    if (α_des = 0) then
        if (α_{t-1} = 0) then
            Auto mode is activated
        else
            Transition mode 2 is activated
        end if
    else
        if (α_{t-1} < 1) then
            Transition mode 1 is activated
        else
            Manual mode is activated (α = 1)
        end if
    end if
end if
```

4. SYSTEM'S VALIDATION

The simulation tools used in the validation are presented in this section. Validation is done on the"*SCANeR Studio*" (OKtal) simulator by co-simulation between the later and Matlab/Simulink. Then, the simulation results of two scenarios are presented later to show the effectiveness of the proposed shared lateral control including the transition system.

4.1 Simulation tools

-SCANeR Studio simulator: "*SCANeR Studio*" simulator is a simulation platform answering the demand of researches and engineers. This simulator allows user to create a safe and controllable environment for the validation of different scenarios with the different driving conditions (Fig.4). A Scaner vehicle model is used on this software, with the different driving modes: Autonomous and Manual modes and the 2 modes of transition system. Thus, The "*SCANeR Studio*" simulator is used in this work to validate the proposed shared control that interacts with the human driver through the "*Logitech G29*" (see Fig.6).

- Matlab/Simulink: The co-simulation is done on *Matlab/Simulink*, by developing the different Simulink blocks in Fig.5. The "*Logitech G29*" (Fig.6) is the steering wheel that permits the interaction between driver input with the "*SCANeR Studio*" simulator. The wheel can rotate up to 900°, corresponding to 60° on the wheels. It has three pedals and a dual motor force feedback with a overheat safe guard. All these features make the driving more realistic for the users. In addition, the different blocks for the autonomous controller, localization, etc., are developed on Matlab/Simulink.

4.2 Simulation results

After preparing the simulation environment to validate the proposed shared control, validation is done on "*SCANeR Studio*" simulator, by using the test track given in the Fig.7. The vehicle realizes the path following maneuver by cooperating with the human in two different scenarios discussed in the following. Note that $\delta_{threshold}$=1.2 *rad* for the 2 scenarios.

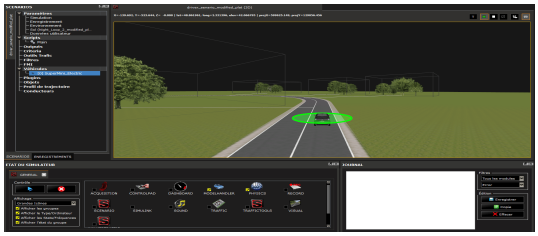

Fig. 4. The *SCANeR Studio* environment.

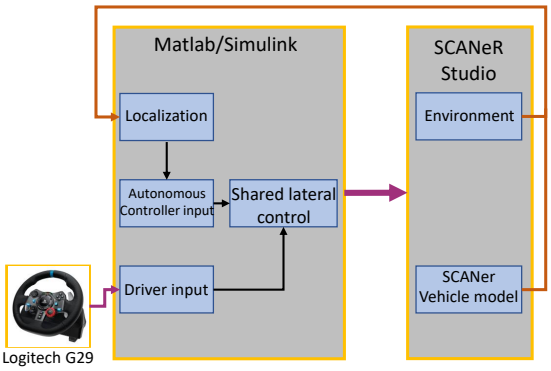

Fig. 5. Co-simulation between *Matlab/Simulink* and *SCANeR Studio*.

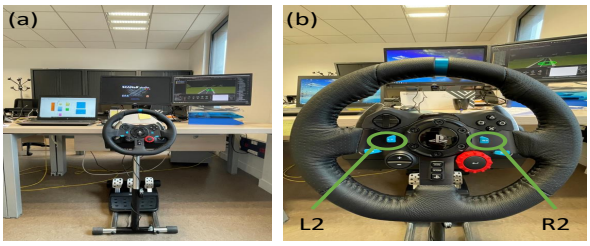

Fig. 6. The steering wheel hardware, Logitech *G*29.

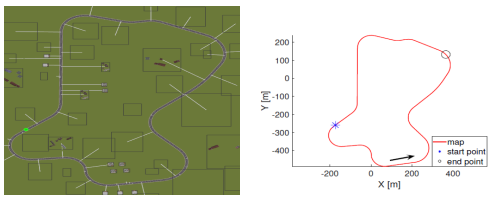

Fig. 7. Map of the test track.

-Scenario 1: This scenario shows the transition between the auto and manual modes depending on the driving situations. The transition is able to switch from one to another mode by ensuring road safety and enhancing driving performance. The driver's availability is full for the overall trajectory (see Fig.8). The driver demands a take over request (TOR=1 at t=8.5s) by pressing the $R2$ bottom and $\alpha_{des} = 1$ because the driver's availability is equal to 1 and there is no conflict on the driver's behaviors (eq.9). For that, α increases from 0 to 1 in 1.5s at t=10s according to the transition mode 1 of transition system. The driver takes the action of vehicle's control until t=32s. At t=32s, there is a conflict on driver's behaviors (see. Fig.9) and α_{des} becomes 0. For that, α decreases again to 0 in 0.2s to penalize the driver, and the driving will be fully autonomous, according to the transition mode 2. Again at t=50s the driver still asking a take over action and $\alpha = 1$ because the conditions of activation of transition mode 1 are realized. The driver acts on the vehicle's control until t=70s and finally he decides to switch off the manual mode by pressing the $L2$ bottom and α=0 at t=70s. The different values of α are given in the Fig.8, which shows that the lateral error is between $-40cm$ and $+40cm$, that means the cooperation of driver with the autonomous system leads to an acceptable and accurate lane keeping with a small lateral error. The steering angles on the wheels of Auto, Manual and shared modes are given in the Fig.9. As we can see in Fig.9, a smooth switching is done between the two agents to ensure the transition between them and compensate the conflict of driver's behaviors, that makes the system stable. Finally, the Fig. 10 shows the longitudinal speed which tracks the desired one using the STSM controller, the road curvature of the desired track and finally the lateral and longitudinal

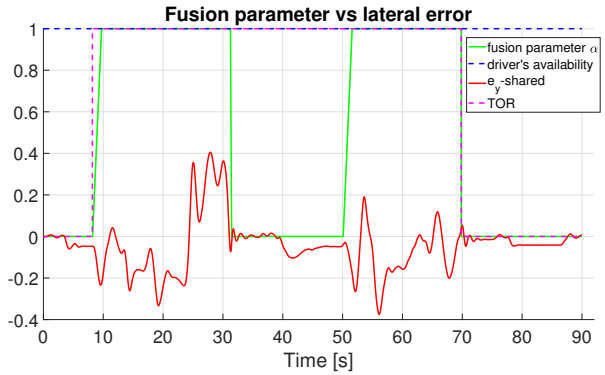

Fig. 8. The lateral error - S1

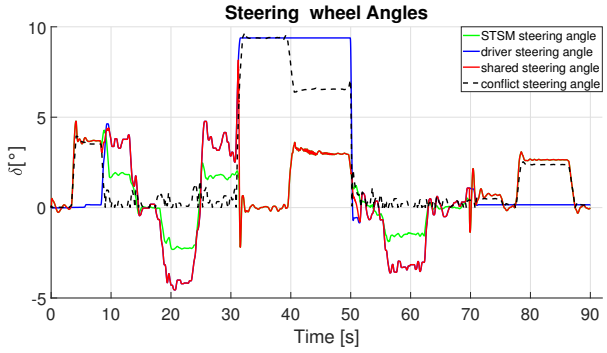

Fig. 9. The different steering wheels angles - S1

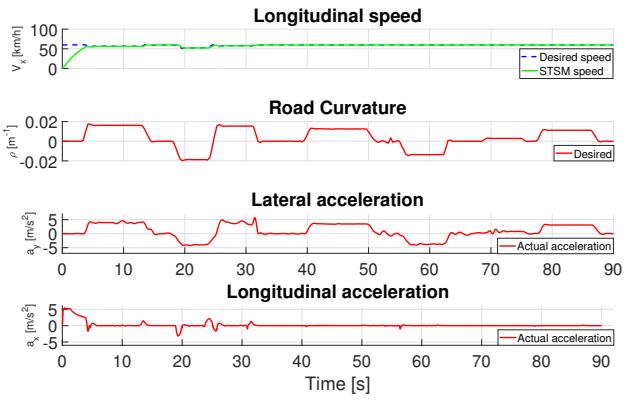

Fig. 10. Vehicle dynamic variables - S1

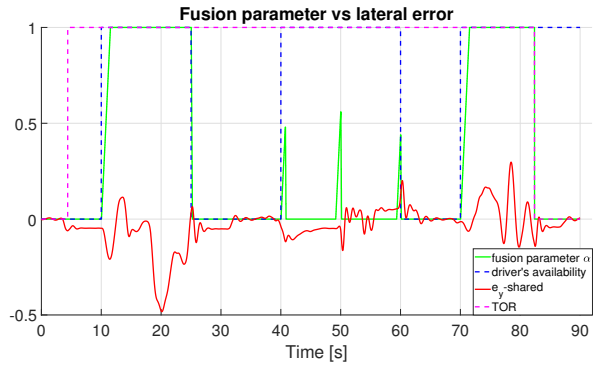

Fig. 11. The lateral error - S2

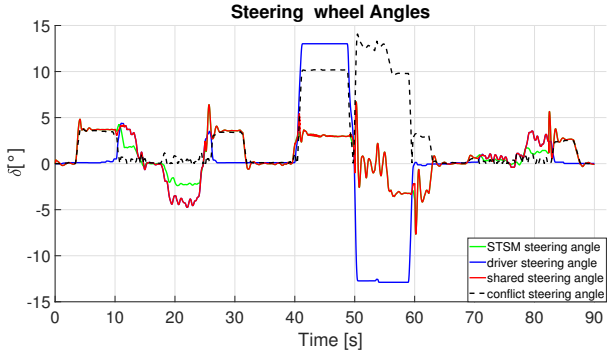

Fig. 12. The different steering wheels angles - S2

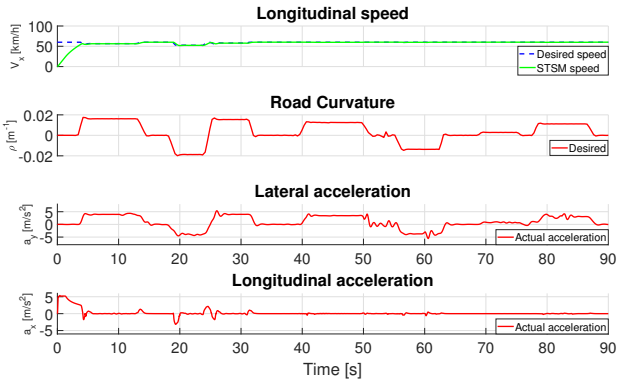

Fig. 13. Vehicle dynamic variables - S2

accelerations. The actual lateral acceleration does not exceed the $\pm 5m/s^2$, which corresponds to a comfortable driving zone. In addition, the actual longitudinal acceleration is pertinent ($< \pm 3m/s^2$) for a comfortable maneuver. To conclude, the Scenario 1 proves that the transition between the two agents is possible while maintaining a comfortable driving against the switching between the different modes and enhancing safety on the road.

-Scenario 2: This scenario is defined to deal with the variation of different variables (DA, $\delta_{conflict}$, α_{des}, TOR). The transition system is adapted against this variation to show the functionality of this system. The management between the different modes under varying driving conditions is presented here. Refer to Fig.11, the driver asks the take over action permission at t=5s, however this action is not approved until t=10s where the driver's availability is full (see Fig. 11) and $\alpha_{des} = 1$. α starts to increase and the driver takes totally control at t=11.5s. He is still acting on the vehicle's control until t=25s, where the DA is lost ($\alpha_{des} = 0$) and the auto mode is switched on to drive the vehicle until t=40s. At t=40s, the driver retains the vehicle's control because the DA is equal to 1 again ($\alpha_{des} = 1$) and α starts to increase. During this phase, there is a conflict that occurs on the driver's behaviors (α_{des} becomes 0) and the value 1 for α is not reached. α will decrease again to 0 to give the control authority to the autonomous system in case the driver is not able to drive the vehicle. For the same reasons, α has the same behavior around t=50s. In addition, α=0 at t=60s even though the conflict on the driver's behaviors starts to decrease (see Fig.12), but the driver's availability is equal to 0 again and $\alpha_{des} = 0$ (eq.9) at t=60s. The increase of DA at t=70s leads to increasing in the α value. The driver drives his vehicle from t=70s to t=83s when he decided to switch on the Auto mode (TOR=0) and take his rest. The parameter α is given in the Fig.11. As shown in Fig.11, the different transitions lead to a small lateral error that guarantees the driving safety in terms of vehicle's stability during the lane keeping. Fig.12 shows the different steering angles on the wheels. The transition between the manual and auto modes is smooth and safe specially during the switching (at t=25s, 40s, 70s for example). As we can see in the Fig.13, there is a good tracking for the desired longitudinal speed. The actual lateral and longitudinal acceleration are limited between $\pm 5m/s^2$ and $\pm 3m/s^2$ respectively, which confirm the passenger's comfort. Thus, the driving is safe and comfortable despite the variation of driving conditions and the switching between the three modes: auto, manual and transition system's modes.

5. CONCLUSION AND PERSPECTIVES

To conclude, in this paper a shared lateral control has been developed to ensure the transition between the human driver and the automated system. The different driving modes including the transition system are detailed in this work. Then, the shared lateral control architecture is presented to blend the two control inputs. A decision making algorithm is developed, using a coordinator for the control authority allocation and driving modes determination. The proposed shared control is validated on the "*SCANeR Studio*" (OKtal) professional simulator interacting with human driver through the "*Logitech G29*" steering wheel. The validation is done for the two scenario of lane keeping maneuver. The results show the effectiveness of the proposed approach to ensure a smooth transition and promote road's safety. In the future work, we will consider other criteria to prove the effectiveness of the decision making process during the transition phase.

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Appendix A. REDUCED VEHICLE MODEL

The vehicle model is based on a robotic formalism model presented in Chebly et al. (2019), Chebly (2017). However, to simplify the controller design, some assumptions are given in Chebly et al. (2019). With all assumptions, the reduced vehicle model used to establish control laws, can be written as:

$$
\begin{aligned}
& m_e\ddot{x} - m\dot{y}\dot{\psi} + L_3\dot{\psi}^2 + F_{aero} \\
& + \delta(2C_{\alpha_f}\delta - 2C_{\alpha_f}\frac{\dot{x}(\dot{y}+L_f\dot{\psi})}{\dot{x}^2-(\frac{E}{2}\dot{\psi})^2}) = g_1 \\
& m\ddot{y} + m\dot{x}\dot{\psi} - L_3\ddot{\psi} \\
& + 2C_{\alpha_f}\frac{\dot{x}(\dot{y}+L_f\dot{\psi})}{\dot{x}^2-(\frac{E}{2}\dot{\psi})^2} + 2C_{\alpha_r}\frac{\dot{x}(\dot{y}-L_r\dot{\psi})}{\dot{x}^2-(\frac{E}{2}\dot{\psi})^2} = g_2 \\
& I_3\ddot{\psi} + 2L_fC_{\alpha_f}\frac{\dot{x}(\dot{y}+L_f\dot{\psi})}{\dot{x}^2-(\frac{E}{2}\dot{\psi})^2} \\
& - 2L_rC_{\alpha_r}\frac{\dot{x}(\dot{y}-L_r\dot{\psi}))}{\dot{x}^2-(\frac{E}{2}\dot{\psi})^2} - L_3(\ddot{y}+\dot{x}\dot{\psi}) = g_3
\end{aligned}
\tag{A.1}
$$

where x and y are the longitudinal and the lateral positions of the vehicle at its center of gravity (COG). ψ is the yaw angle. F_{aero} is the longitudinal aerodynamic force. m_e, g_1, g_2 and g_3 are given by:

$$
\begin{aligned}
m_e &= m + 4\frac{I_w}{R_{eff}^2}, \\
g_1 &= \frac{\tau_w}{R_{eff}}, \\
g_2 &= (2C_{\alpha_f} - 2\frac{I_w}{R_{eff}^2}\ddot{x})\delta, \\
g_3 &= L_f g_2 + (-\frac{E}{2}C_{\alpha_f}\frac{E\dot{\psi}(\dot{y}+L_f\dot{\psi})}{\dot{x}^2-(\frac{E}{2}\dot{\psi})^2})\delta.
\end{aligned}
$$

The control inputs to the vehicle are the steering wheel angle, δ, and the Driving/Braking wheels torque τ_w. More details about the vehicle parameters are given in Chebly et al. (2019).