Reset control with sector confinement for a lane change maneuver

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***Abstract*—The new features that are being added today in cars for assisted or autonomous driving tasks require a specific study that allows these tasks to be performed efficiently. Among these tasks, in this work the application of advanced control methods for the lane change maneuver is studied, obtaining better results than the classic methods which are inherently limited to fundamental limitations of the linear systems. An application of the reset method based on the linear confinement of trajectories is presented, which allows to reduce the error to zero quickly. This method is compared by simulation with another reset control method, the reset control with optimal reset. And then, the method is validate in CarSim.**

***Index Terms*—Lane change maneuver, autonomous driving, control reset, optimal reset, sector confinement.**

I. Introduction

Today's vehicles implement more often assistance systems which allow a more safety driving such as pedestrian detection (PD), automatic cruise control (ACC), lane change warning (LDW), lane maintenance assistant (LKA) and lane change assistant (LCA), and so on. Gradually, they are also equipped with new features for autonomous driving. Developments in this field lead to improvements in many aspects of transport systems, such as road safety, traffic congestion, traffic efficiency and reduced fuel consumption. According to some forecasts, the increasing independence, accuracy and efficiency of autonomous vehicles will lead, by the end of this decade, to a limited availability of automated driving functions. It is expected that, by 2040, autonomous vehicles will be equipped with a wide variety of highly automated functions [1].

Within the functionalities of autonomous driving there are those of lane changing and lane keeping which have been thoroughly studied due to its paramount importance for a self-driving intelligent vehicle, as it is evinced by the numerous articles existing in the literature. In addition to being fully operational for critical situations where safety is at risk, autonomous vehicles must be able to move in compliance with a set of comfort requirements of acceleration and jerk, see [2].

By other hand, a reset controller is merely a conventional regulator endowed with a reset mechanism which is a strategy that resets to a certain value one or several of the controller states, provided that a certain condition is met. The event that triggers the resetting action is usually the zero-crossing of the controller input, although other choices are possible as well. Reset control was introduced the Clegg Integrator (CI) by Clegg in 1958 [3] and it was discontinued until 1975 when Horowitz and Rosenbaum introduced the first order reset element (FORE) [4]. In these works it is remarked that the reset control overcome the fundamental limitations that affect to the linear systems [5]. Later, in 90s, Beker [6] introduced certain stability condition for finite-dimensional systems based on Lyapunov functions. And more recently, several authors have analyzed the behavior of systems with different reset strategies.

Several control methods used for lane change maneuver can be found in the literature. For example, MPC is a widely used control method in this field, obtaining good results, especially, for aggressive maneuvers where actuator constraints concerning the physical limits (amplitude and slew rate limits) such as the works [7] [8] [9]. In [10], a fuzzy control for an automated lane-keeping system is presented. A fuzzy gain scheduling is employed to tune the steering controller. In [11] a sliding mode control (SMC) is presented, it produces a smooth lane change suitable for use in an Automated Highway System. In [12] the authors use an active steering assistance system for heavy vehicles based on sliding-mode observers. [13] proposes a disturbance compensation for an evasive preventive pedestrian protection system. [14] presents a robust output-feedback control considering network-induced delay and tire force saturation. [15] introduces an active disturbance rejection control (ADRC) to guarantee robustness against vehicle uncertainties and external disturbances. Some linear control approaches are also considered in [16] [17] [18]. Some methods can be checked in articles with several comparisons as [19] and [20].

The main contribution of this work is to apply the reset control with sector confinement strategy developed in [22] to the lane change maneuver, and to compare the results with the best strategy among the linear and non linear analyzed in [21], optimal reset control based on the minimization of the integral sqaure error (ISE).

Finally, it is necessary to introduce the CarSim software as it will be used to validate the results obtained by simulation. CarSim (Version 2017, Mechanical Simulation Corporation, Ann Arbor, MI, USA) is deemed a standard in the automotive industry. It is used for analyzing vehicle dynamics and assessing performance and it is endowed with a large database of vehicles and automotive elements. Due to its highly reliable models, CarSim is widely used as seen in numerous publications [23]–[25].

The article is organized as follows. In Section 2, the model of the vehicle used for the lane change maneuver is introduced. In Section 3, the design of the control method employed is presented. Then, in Section 4 the simulation of the control method proposed is made, comparing it with other control method. After that, the control method proposed is validate in CarSim in Section 5. Finally, the conclusions are exposed in Section 6.

II. Dynamic Model

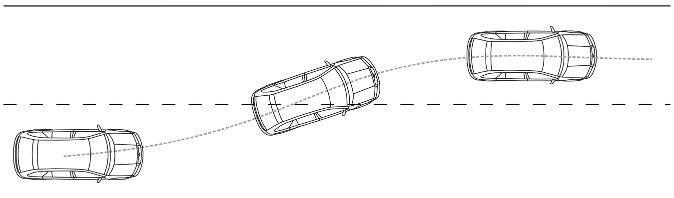

Fig. 1. Lane change maneuver.

The model employed for the vehicle in a lane change maneuver is a dynamic bicycle model. A schematic depiction of the maneuver can be seen in Figure 1. The bicycle denomination has as its source the fact that, as in a bicycle, the model works with the assumption that only two wheels are present, one in the center of each of the two wheel axles. A representation of the bicycle model can be seen in Figure 2.

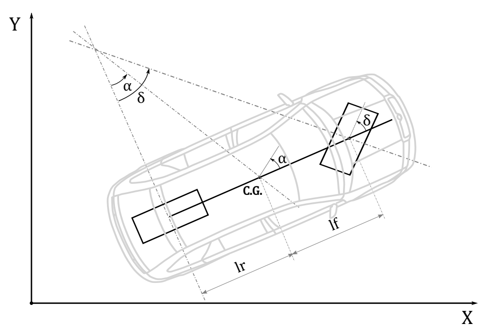

Fig. 2. Physical dimensions of the vehicle.

A detailed description of the whole model and all the intermediate steps and assumptions made to obtain the model can be found in [26]. The parameters included in the resulting linearized model are: vehicle mass (M), yaw inertia (I_z), cornering stiffness of the front wheels (C_f), cornering stiffness of the rear wheels (C_r), wheel angle (δ), distance from the front axle to center of gravity (C.G.) (l_f) and distance from the rear axle to C.G. (l_r). The space-state representation of the model can be seen in Equations (1) and (2).

$$\begin{bmatrix} \dot{Y} \\ \dot{\psi} \\ \ddot{Y} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -2v_x a_{11} & 2a_{11} & 2a_{12} \\ 0 & -2v_x a_{21} & 2a_{21} & 2a_{22} \end{bmatrix} \begin{bmatrix} Y \\ \psi \\ \dot{Y} \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{2C_f}{M} \\ \frac{2C_f l_f}{I_z} \end{bmatrix} \delta \tag{1}$$

$$y = [1 \quad 0 \quad 0 \quad 0] \begin{bmatrix} Y \\ \psi \\ \dot{Y} \\ \dot{\psi} \end{bmatrix} + 0 \tag{2}$$

Y and Ψ are the lateral position and orientation of the car respectively. The coefficients a_{ij} are defined as:

$$\begin{aligned} a_{11} &= -\frac{C_r + C_f}{v_x M} & a_{12} &= \frac{l_r C_r - l_f C_f}{v_x M} \\ a_{21} &= \frac{l_r C_r - l_f C_f}{v_x I_z} & a_{22} &= -\frac{l_r^2 C_r + l_f^2 C_f}{v_x I_z} \end{aligned} \tag{3}$$

The vehicle modeled in this work is a Sedan-D Class, a 4-door utility vehicle with 6-speed automatic transmission, 150 kW engine and R17 215/55 tires. The identified values for this case were got from [21]. These parameters are identified for a empty car as: $M = 1370kg$, $I_z = 2315km/m^2$, $C_f = C_r = 103340N/rad$ $l_f = 1.11m$ and $l_r = 1.67m$. The identified plant for $v_x = 25m/s$ is Equation (4).

$$P(s) = \frac{150.9s^2 + 2501s + 3.774 \cdot 10^4}{s^4 + 26.43s^3 + 216.5s^2} \tag{4}$$

Unfortunately, the plant model depends on the longitudinal speed of the vehicle. To avoid this detrimental effect, a series of filters has been defined which, for each speed, filter out the undesired effects of the speed and the resulting plant is a double integrator, as can be seen in the Figure 3. Therefore, for the tests a system has been established consisting of a controller, filter $F(s)$ and plant $P(s)$ identified in a closed loop. The design of the controller is made for the equivalent double integrator plant. The ideal pre-filter $F(s)$ for the plant $P(s)$ for $v_x = 25m/s$ is defined in Equation (5). The calculation of the filtrate of the plant can be found in a more detailed way in the work [21].

$$F(s) = 0.0078 \frac{s^2 + 23.27s + 164.5}{s^2 + 14.68s + 228.9} \tag{5}$$

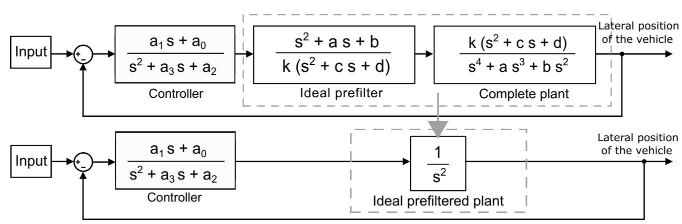

Fig. 3. System control closed loop and system control closed loop equivalent.

III. Control Design

In this section, the main aspects of reset control with sector confinement for lane change maneuver will be introduced. As it was said, a reset controller is equipped with a mechanism that allows a state to be changed when a condition occurs. The advantage of this kind of impulsive systems is that it can be based on a simple linear system, well known for its widespread use, and they are not subjected to the fundamental limitations of linear systems, as it explained in [5].

The reset action in the controller can be modified in several ways to yield the lane change maneuver meeting the design specifications. The method employed in this work has been developed by González et al. in [22]. The idea of this method is similar to the classic reset control where a state is modified when the error signal reaches to a determinate condition. When that reset event occurs, the state of the reset controller is set to other value conveniently calculated. This control technique uses the reset action in one or more of the states of the system to confine the trajectories of the phase plane in a certain sector. It combines continuous flow dynamics with discrete reset jumps to reduce quickly the error to zero. The reset events occur when the error trajectory in the phase plane exceeds certain limits set by the designer. In this case they correspond to the fulfillment of certain geometrical conditions of the phase plane.

Consider the linear plant (P) and a controller (C):

$$P: \begin{cases} \dot{x}_p(t) = A_p x_p(t) + B_p u(t) \\ y(t) = C_p x_p(t) \end{cases} \tag{6}$$

$$C: \begin{cases} \dot{x}_c(t) = A_c x_c(t) + B_c e(t) \\ u(t) = C_c x_c(t) \end{cases} \tag{7}$$

The LTI closed loop model is:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Br(t) \\ y(t) &= Cx(t) \end{aligned} \tag{8}$$

where the state vector is as follows:

$$x(t) = [x_p(t)^\top, x_c(t)^\top]^\top \tag{9}$$

The hybrid system is composed of the linear system (8) with the addition of a reset mechanism. So, the hybrid system dynamics can be decomposed in two different regions at the state space:

- The flow set $\mathbb{F}$ as continuous mode.
- The jump set $\mathbb{J}$ as discrete or impulsive mode.

The phase plane used is given by a modified error variable, denoted by $s(t)$, and it is employed to facilitate the convergence of $e(t) \to 0$. It has a similar behavior as slide variable in SMC method. This modified error is defined by Equation (10) with $\alpha_j \in \mathbb{R}^n$ and $0 \leq q < p$.

$$s(t) = \sum_{j=0}^{q} \alpha_j \overset{(j)}{e}(t) \tag{10}$$

To make possible the confinement sector for $s(t)$ trajectories, the regions of flow and jump are well defined in the phase planes $\left(\overset{(k)}{s}(t), \overset{(k+1)}{s}(t)\right)$ for $k = 0, 1, \ldots, c^* - 1$, where c^* ($c^* \leq c$) are the state number of the controller states which can be used to change the trajectory of $s(t)$. The condition of reset action is given by the relationship between the modified error variable and a geometric limits that delimit the flow sector. The regions established are decisive to set the conditions of the reset and the states value after reset, and as a consequence the desired confinement trajectory. It makes that the modified error $s(t) \to 0$, and therefore $e(t) \to 0$.

The design procedure begins by obtaining the relative grade of the plant r_d, with $1 \leq r_d \leq p$, being p the number of plant states. In this case, the plant with a pre-filter is a second order system. Then, it is necessary to select the base linear controller which produces a stable closed loop system. If a controller is selected with the form of Equation (11), the entire system can be reorganized as it is shown in Figure 4.

$$C(s) = \frac{a_1 s + a_0}{s^2 + a_3 s + a_2} \tag{11}$$

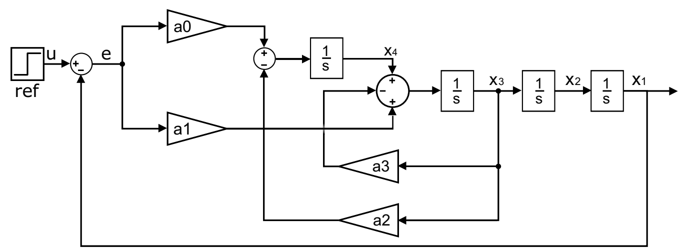

Fig. 4. Reorganization of closed-loop system.

The LTI closed-loop system in state space notation is defined as Equations (12) and (13).

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -a_1 & 0 & -a_3 & 1 \\ -a_0 & 0 & -a_2 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ a_1 \\ a_0 \end{bmatrix} ref \tag{12}$$

$$y = [1\ 0\ 0\ 0] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + [0]u \tag{13}$$

Where x_1 is the position, x_2 is the velocity, x_3 is the acceleration and x_4 is the jerk for the lateral movement of the vehicle. For this case, the parameters of the controller are picked from the previous work [21], because the method exposed will be compared with other reset controller mentioned in that work, and it should be compared in the same conditions. The design requirements of the controller are: $OS = 21.45\%$, $t_r = 5s$ and $t_s = 40s$. With these requirements, the parameters of the tuned controller are: $a_0 = 0.0683$, $a_1 = 0.2571$, $a_2 = 1.4872$, $a_3 = 1.8379$.

Now, it is necessary to define the reference signal to be used. For this case, since it is a step type input signal, it is important to note that its first derivative and those of greater order will be null.

Then, the $\alpha_0, \alpha_1, \ldots, \alpha_q$ are chosen to define the modified error in Equation (10), with $\alpha_0 \neq 0$ and where $q \geq (r_d - 1)$. A good value for these coefficients is given by a Taylor approximation, as detailed in Section 4 of [22].

If $q = 1$, the modified error and its derivative constitute the phase plane $(s(t), \dot{s}(t))$ where the trajectories are confined. For $q = 1$, the $\dot{s}(t)$ only depends on state x_3, Equation (14), and it can be a problem due the jumps of the acceleration state and with the consequent non-linearity of the jerk state.

$$\begin{cases} s(t) = \alpha_0 e(t) + \alpha_1 \dot{e}(t) = \alpha_0(ref - x_1(t)) - \alpha_1(x_2(t)) \\ \dot{s}(t) = \alpha_0 \dot{e}(t) + \alpha_1 \ddot{e}(t) = -\alpha_0(x_2(t)) - \alpha_1(x_3(t)) \end{cases} \tag{14}$$

If $q = 2$, the modified error and its derivative are defined in Equation (15). $\dot{s}(t)$ depends on the two states of the compensator, then, the reset action can be carried out in the x_4 state. In this way, the acceleration state is not directly modified, and the jerk has bounded values for all experiment.

$$\begin{cases} s(t) = \alpha_0 e(t) + \alpha_1 \dot{e}(t) + \alpha_2 \ddot{e}(t) = \alpha_0(ref - x_1(t)) - \\ \quad \alpha_1(x_2(t)) - \alpha_2(x_3(t)) \\ \dot{s}(t) = \alpha_0 \dot{e}(t) + \alpha_1 \ddot{e}(t) + \alpha_2 \dddot{e}(t) = -\alpha_0(x_2(t)) - \\ \quad \alpha_1(x_3(t)) - \alpha_2(-a_1 x_1(t) - a_3 x_3(t) + x_4(t) + a_1 ref) \end{cases} \tag{15}$$

In next step, a region must be selected where the trajectories will be maintained in. This is achieved by using a pair of boundary lines that limit a section of the $(s(t), \dot{s}(t))$ plane, these lines are defined with $\lambda_F \dot{s} = s$ and $\lambda_Z \dot{s} = s$, upper and lower boundaries respectively. And another central line to which the trajectory will be taken in the event of a jump defined as $\lambda_M \dot{s} = s$. Then, the slopes of the lines must meet $\lambda_F < \lambda_M < \lambda_Z$ (in absolute value). A good choice for design is that the central line corresponds with the bisector of the other two lines.

Once the lines have been defined, the controller must be properly implemented so that it takes the trajectory to the center line whenever the trajectory leaves the allowed region, delimited by the boundary lines that define the flow region in the phase plane $(s(t), \dot{s}(t))$.

Finally, the new value of x_4 in the jump event is denoted by x_4^+ and, for this case, it is obtained by Equation (16). As it can be seen, the control method does not require large computing resources.

$$x_4^+ = \frac{(s/\lambda_M) - \dot{s} - \alpha_2 x_4}{-\alpha_2} \tag{16}$$

To guarantee the stability of the system, it is necessary to check two conditions: the lyapunov's condition in flow mode given by the LMI of Equation (17), and the Lyapunov's condition in jump mode, that is Equation (18). If the LMI is feasible the control can be applied, otherwise it is necessary to redefine the slopes of the lines. For more extensive information on the method for interested readers, in [22] all conditions are well defined and the choice of parameters is explained more extensively.

$$\tilde{S}^\top I_v + I_v \tilde{S} - \sum_k \tau_k I_{\lambda_k} \leq 0 \tag{17}$$

$$x_j^\top Q_j x_j + 2 s^{-\top} Q_s x_j \leq 0 \tag{18}$$

IV. SIMULATION

In order to give an overview of the method, two set of parameters are selected to test the control method. The first set of parameters (Set 1), for a aggressive behavior, are:

$$\begin{gathered} \alpha_0 = 1, \qquad \alpha_1 = 1.2, \qquad \alpha_2 = \frac{\alpha_1^2}{2} \\ \lambda_M = -\frac{2}{\alpha_1}, \quad \lambda_F = \frac{\lambda_M}{2}, \quad \lambda_Z = 2\lambda_M \end{gathered} \tag{19}$$

This first set of parameters makes the jerk signal jump very abruptly, contradicting the comfort limits of the maneuver of 1 m/s^3 (see [2]). As it can be observed in Figure 5, the jerk exceeds the limit. To get a smoother behavior leaving the controller unchanged, it is necessary to increase the confinement area, changing the slopes λ_F and λ_Z. As the parameters depends on α_1, the second set of parameters are defined as in (19) but $\alpha_1 = 4$. This action makes the rise time and settling time worse but the jerk peak remains below comfort limits. The selection of parameters could be improved but this example is presented to clearly show the difference when changing a parameter in the method. The phase plane of pseudo-error $(s(t), \dot{s}(t))$ with sector confinement of the two different parameter sets are shown in Figures 6 and 7.

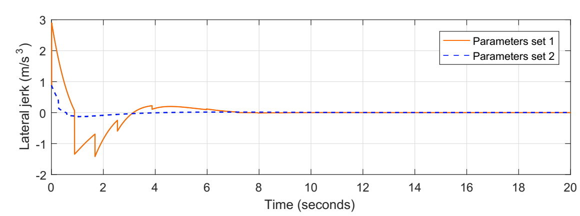

Fig. 5. Jerk response for parameter set 1 and 2.

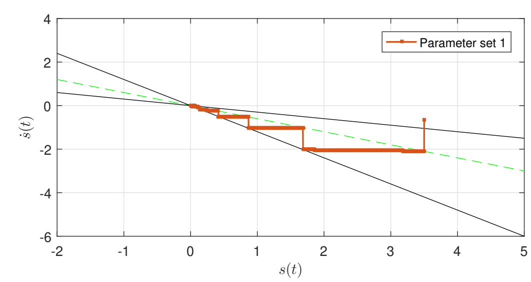

Fig. 6. Trajectory of system in phase plane $(s(t), \dot{s}(t))$ for parameter set 1.

To compare the response of the proposed controller with parameter set 2, the responses obtained for the lane change maneuver are shown along with the best method among all linear and non-linear methods analyzed in [21] under the same conditions. In the Figure 8, it can be observed a comparison of the proposed method with the results obtained with the optimal reset with variable band method, the best control method of the mentioned article.

In the case of reset control with sector confinement, it can be said that it is a control method that achieves a good temporal

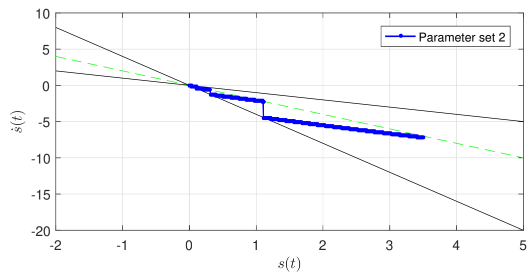

Fig. 7. Trajectory of system in phase plane $(s(t), \dot{s}(t))$ for parameter set 2.

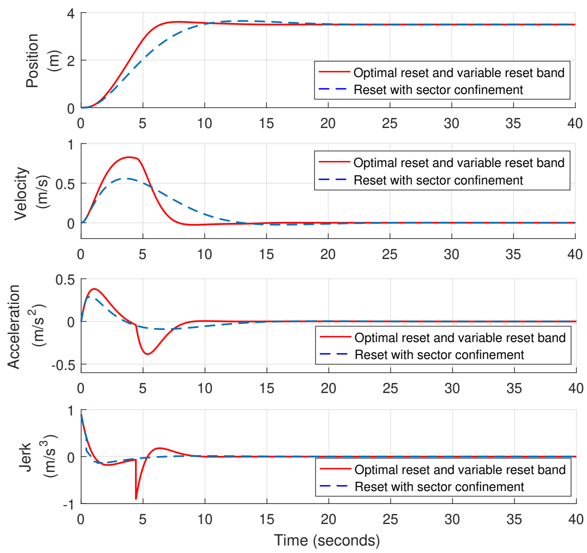

Fig. 8. Simulation of the lane change maneuver with the reset control strategies proposed.

response, although due to the imposition of comfort limits it is not as effective as the control methods with optimal reset developed in [21]. It is important to say that this method is robust against parametric changes and therefore can be said to be a good candidate for the lane change maneuver.

V. Validation with CarSim

To validate the control method simulated in the last section of the article, a setup on CarSim is implemented (Figure 9). For that, the plant (double integrator) is replaced by a pre-filter and the CarSim block.

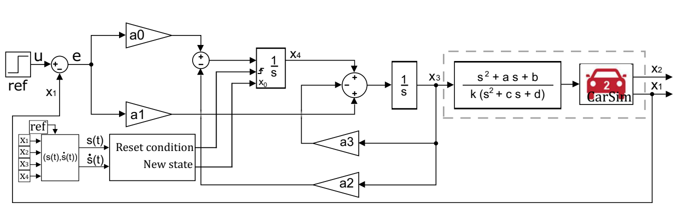

Fig. 9. Lane change maneuver validation setup.

For the validation, it was decided to focus the comparison of the reset with sector confinement with the reset control method with best results presented in [21]. The Figure 10 shows the position, velocity, acceleration and jerk for the lane change maneuver obtained in CarSim software.

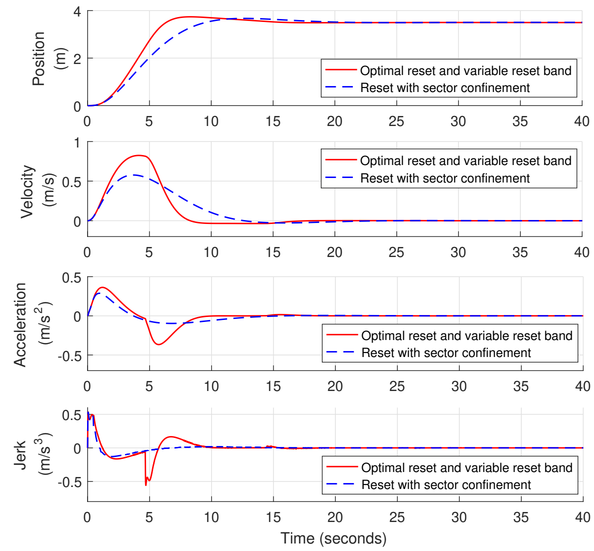

Fig. 10. Validation of the lane change maneuver in CARSIM.

In the figure, it can be appreciated that the responses of system with different control method present a greater overshoot and larger settling time than in the simulation case. This may be because pre-filtering is not ideal, so the plant is not exactly a double integrator, but the response of the system corresponds qualitatively with the simulation.

As it can be seen, the reset control method with sector confinement can be employed for lane change maneuver because the response obtained, without reaching the limits of jerk, is comparable to that obtained with the other method of control reset as it can be seen in Table I. Therefore, it can be a viable alternative to be used in this task.

TABLE I
VALIDATION CHARACTERISTICS OF THE CONTROLLERS

Controller	ISE	$\int e(t)$	t_r (s)	t_s (s)	0S (%)
Optimal reset and variable band	36.087	11.964	3.799	13.749	6.866
Reset with sector confinement	42.204	15.091	5.891	17.151	4.768

To test the robustness of the reset control with sector confinement, other experiment is presented. It corresponds to the lane change maneuver with variable longitudinal speed (see Figure 12). As it can be seen in Figure 11, the control method works well for changes in system parameters.

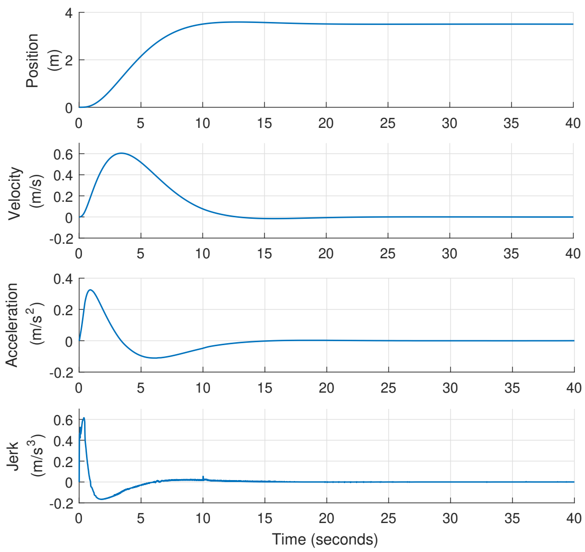

Fig. 11. Experiment with reset control with sector confinement and variable longitudinal velocity.

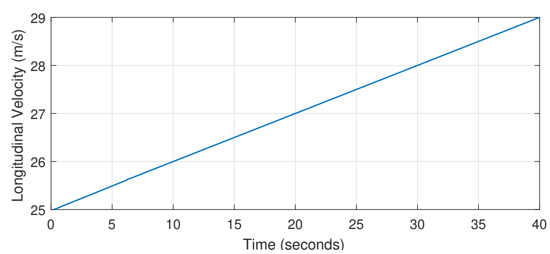

Fig. 12. Longitudinal velocity of the vehicle in the lane change maneuver.

VI. Conclusions

A reset control system has been designed for efficient lane change maneuvering taking into account the particularities of the plant, in this case the dynamic model of a vehicle. The reset control with sector confinement has been compared with an advanced reset control method obtaining good results.

With the reset with sector confinement method used in this work, good results are obtained in spite of the fact that the control action is limited by the permissible jerk value due to the comfort limitations.

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