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ACC of a Commercial Vehicle Using Fractional Order Controllers for Throttle and Brake

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Abstract— **Recently, many commercial systems have been designed for adaptive cruise control (ACC) manœuvres to increase safety during driving. The aim of this paper is twofold. Firstly, based on a previous fractional order speed control, an improved fractional order control is presented to control a commercial Citroën C3 prototype –which has automatic driving capabilities– at low speeds, which considers a hybrid model of the vehicle. Specifically, two different fractional order PI$^{\alpha}$ controllers are designed to act over the throttle and brake pedals, respectively. Secondly, a stop-and-go manœuvre is implemented with two different distance policies using two cooperating vehicles at low speeds. In this manœuvre, the objective is to maintain a desired interdistance between the leader and follower vehicles, i.e., to perform a distance control –with a PD controller in this case–, in which the previous PI$^{\alpha}$ controllers are used for the vehicle longitudinal control. Experimental and simulation results, obtained in a real circuit, are given to demonstrate the effectiveness of the proposed strategies for ACC manœuvres at low speeds.**

I. Introduction

Research on traffic safety is continuously developing and carried out around the world. In particular, the aim is to develop active systems, called advanced driver assistance systems (ADAS), which will be able to prevent accidents. One of the systems included in commercial vehicles to increase safety in carrying out driving-related tasks is adaptive cruise control (ACC). ACC technology improves upon the function of standard cruise control (CC) by automatically adjusting the vehicle speed in order to maintain a proper distance with the leader vehicle in a cooperative matter using vehicular communication. Refer to e.g. [1],[2],[3] for a survey on recent research in the field.

However, ACC commercial systems work at speed greater than 30km/h. Capable and efficient systems for low-speed ACC, which is sometimes called stop-and-go ACC, remains unknown in the specialized literature [1]. At the same time, today's better understanding of the potentialities of fractional order control (FOC) and the increasing number of studies and applications in many areas of science and engineering have led to its recognition [8]. The control of this kind of manœuvres, which are one of the main drawbacks in the transportation research field, by using fractional order strategies, is the aim of this work.

This paper can be divided into two different parts. In the first part, the CC of the commercial Citroën C3 vehicle is addressed. As a matter of fact, based on a hybrid model of the vehicle, which considers different models for vehicle dynamics when accelerating and braking, two fractional order PI$^{\alpha}$ controllers are designed for CC manœuvres at low speeds. Once CC is achieved, the goal is to control the distance between two vehicles at low speeds in a safe way. Hence, the stop-and-go manœuvre is performed by using the previously designed PI$^{\alpha}$ controllers. A PD controller is tuned to control the vehicle inter-distance.

The rest of the paper is organized as follows. Section II addresses the fractional order CC of the vehicle acting over the throttle and brake pedals. In Section III, ACC manœuvre is described, as well as the inter-distance policy performed in this work. Simulation and experimental results are given in Section IV to validate the proposed CC and ACC strategies. Finally, concluding remarks are included in Section V.

II. Cruise Control

As commented previously, the goal of this part is to design and implement fractional order controllers for the CC at low speeds of a vehicle with automatic driving capabilities –a commercial convertible Citroën C3 Pluriel described in [12]– so as to check its behavior in an environment as real as possible. To do so, different vehicle dynamics are considered, referred to the dynamics acting over the throttle and the one during braking, obtained from experimental results.

In this respect, a linearized dynamic model of the vehicle when accelerating was identified in [4], given by the following first order transfer function:

$$G(s) \simeq \frac{4.39}{s+0.1746}. \tag{1}$$

In order to identify the model during braking, the brake action on the vehicle velocity is depicted in Fig. 1 applying different voltages –from 1 to 4V– to its valve. As can be observed, vehicle dynamics depends on the voltage applied to the brake pedal. These braking dynamics can be given by the following uncertain transfer function:

$$G(s) \simeq \frac{1}{\tau s+1}, \tag{2}$$

where the time constant τ varies with the action over the brake in the interval $\tau \in [1.6, 3.1]$s.

Next, the design process of the fractional order controllers for the throttle and brake pedals are described.

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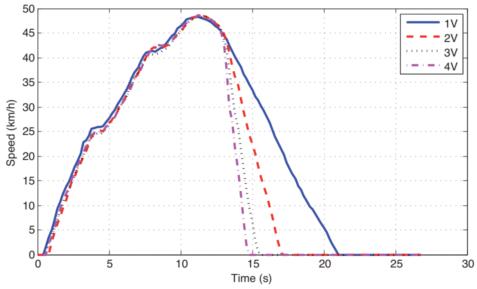

Fig. 1: Velocity dynamics during brake action.

A. Throttle Control

The most important mechanical and practical requirements of the vehicle to take into account during the design process are the following:

- The control action has to belong to the interval $(-1,1)$, where the negatives values means a brake action and the positives, a throttle action.
- The vehicle response has to be smooth to guarantee that its acceleration will be less than the well-known comfort acceleration, that is, less than 2m/s^2.

In previous works, some traditional PI controllers have been designed (refer e.g. to [5]), and in [4] a fractional order PI controller was proposed. A fractional order PI controller can be represented as follows:

$$C(s) = k_{p_1} + \frac{k_i}{s^\alpha} = k_{p_1}\left(1+\frac{z_c}{s^\alpha}\right), \text{ with } z_c = k_i/k_{p_1}. \quad (3)$$

Let assume that the gain crossover frequency is given by ω_c, the phase margin is specified by φ_m and the output disturbance rejection is defined by a desired value of a sensitivity function $S(s)$ for a desired frequencies range. For meeting the system stability and robustness, the three specifications to fulfill are the following:

1. Phase margin specification:
$$Arg[G_{ol}(j\omega_c)] = Arg[C(j\omega_c)G(j\omega_c)] = -\pi + \varphi_m. \quad (4)$$
2. Gain crossover frequency specification:
$$|G_{ol}(j\omega_c)| = |C(j\omega_c)G(j\omega_c)| = 1. \quad (5)$$
3. Output disturbance rejection for $\omega \leq \omega_s =$ 0.035rad/s:
$$|S(j\omega)|_{dB} = \left|\frac{1}{1+C(j\omega)G(j\omega)}\right|_{dB} \leq -20dB, \ \omega \leq \omega_s. \quad (6)$$

Using these three specification and solving the following equations the controller parameters will be obtained [4].

$$z_c = \frac{-\tan\left[\arctan\left(\frac{\omega_c}{p}\right)+\varphi_m\right]}{\omega_c^{-\alpha}\left\{\sin\phi + \cos\phi\tan\left[\arctan\left(\frac{\omega_c}{p}\right)+\varphi_m\right]\right\}}. \quad (7)$$

$$\frac{Kk_{p_1}\sqrt{\left(1+z_c\omega_c^{-\alpha}\cos\phi\right)^2+\left(z_c\omega_c^{-\alpha}\sin\phi\right)^2}}{\sqrt{\omega_c^2+p^2}} = 1$$

$$k_{p_1}^2 + k_i^2\omega_c^{-2\alpha} + 2k_{p_1}k_i\omega_c^{-\alpha}\cos\phi = \frac{\omega_c^2+p^2}{K^2}. \quad (8)$$

$$|S| = \left|\frac{1}{1+k_{p_1}\left[1+z_c\omega^{-\alpha}\cos\phi - jz_c\omega^{-\alpha}\sin\phi\right]\left(\frac{K}{j\omega+p}\right)}\right|. \quad (9)$$

Solving the set of equations (7), (8) and (9) with the Matlab function *fsolve*, the values of the controller parameters are: $k_p = 0.09$, $k_i = 0.025$ and $\alpha = 0.8$.

B. Brake Control

As mentioned before when the brake is active the dynamics of the car is different and needs its own controller. In order to have a robust controller for the uncertain model identified in (2) a robust fractional order PI controller is used. The parameters are tuned based on the method proposed in [7]. Several design specifications should be met by the fractional compensated system in order to be more robust to time constant changes. For the purpose of robustness to time constant variations, the gain and phase margins have been taken as the main indicators. Gain and phase margins have always served as important measures of robustness. It is known from classical control that the phase margin is related to the damping of the system and therefore can also serve as a performance measure. Thus, the specifications to meet are the ones in (4) and (5), referred to phase margin (ϕ_m) and phase crossover frequency (ω_{cp}) specifications, and the one referring to gain margin (M_g), that is:

$$Arg\left(C(j\omega_{cg})G(j\omega_{cg})\right) = -\pi, \quad (10)$$
$$\left|C(j\omega_{cp})G(j\omega_{cp})\right|_{dB} = 1/M_g. \quad (11)$$

where, ω_{cg} is the gain crossover frequency. Thus,a set of four nonlinear equation (4, 5, 10, 11) with four unknown variables $(k_{p_1}, T_i, \alpha, \omega_{cg})$ has to be solved by using the optimization method proposed before. Again, the condition of no steady-state error is already fulfilled with the introduction of the fractional integrator. In order to fulfill the acceleration limitation and concerning to the previous work [4], [5], the specifications i.e. ϕ_m, ω_{cp} and M_g are set as 90deg, 0.3 and 4, respectively, which yield the following values for the controller parameters: $k_{p_1} = 0.07$, $k_i = 0.11$ and $\alpha = 0.45$. It should be mentioned that both velocity and brake control inputs are normalized to $[-1,1]$. Fig. 2 shows the Bode plots of the controlled system by applying the designed controller. As it can be observed, the cross over frequency is $\omega_{cp} =$

Controller for	k_{p1}	k_i	α
Throttle	0.09	0.025	0.8
Brake	0.07	0.11	0.45

TABLE I: Parameters of the PI$^{\alpha}$ controller for CC

0.7rad/s and the phase margin is $\phi_m = 93$deg, fulfilling the design specifications. Moreover, the system is robust to the time constant variation, which is also fulfilled as illustrated in Fig. 3.

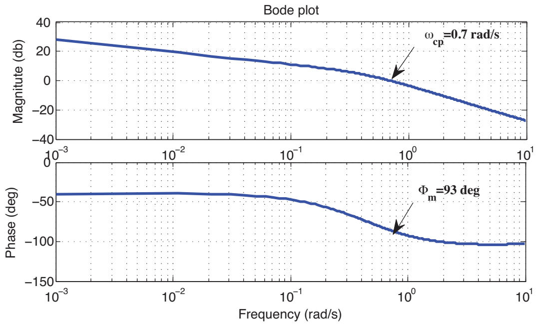

Fig. 2: Bode plot of the controlled vehicle by applying the designed PI$^{\alpha}$ brake controller

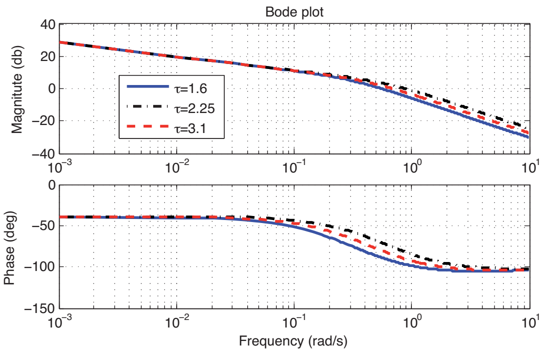

Fig. 3: Comparison of Bode plots of the controlled vehicle by applying the designed PI$^{\alpha}$ brake controller with different values of τ

Table **??** summarizes the parameters of the controllers for brake and throttle control.

C. Digital implementation of fractional order controllers

It has to be taken into account that a fractional order controller is an infinite-dimensional linear filter, and that all existing implementation schemes are based on finite-dimensional approximations. In practice, we use a digital method, specifically the indirect discretization method, which requires two steps: firstly obtaining a finite-dimensional continuous approximation, and secondly discretizing the resulting s-transfer function. In our case, in order to preserve the integral effect, the integral part $s^{-\alpha}$ has been implemented as follows:

$$\frac{1}{s^{\alpha}} = \frac{1}{s}s^{1-\alpha}.$$

Therefore, only the fractional part $R_d(s) = s^{1-\alpha}$ has been approximated.

To obtain a finite-dimensional continuous approximation of the fractional order differentiator, the modified Oustaloup's method is used (see e.g. [8]). Thus, an integer order transfer function that fits the frequency response of $R_d(s)$ in the range $\omega \in (10^{-3}, 10^{3})$ is obtained with 7 poles and 7 zeros. Later, the discretization of this continuous approximation is carried out by using the Tustin rule with a sampling period $T_s = 0.2s$ -GPS sampling period-, obtaining the following digital IIR filters:

- Throttle controller:

$$R_T(z) = \frac{\sum_{k=0}^{7} b_k z^{-k}}{1 + \sum_{k=1}^{7} a_k z^{-k}}, \qquad (12)$$

  where $b_0 = 0.1573$, $b_1 = 0.1325$, $b_2 = -0.4389$, $b_3 = -0.3658$, $b_4 = 0.406$, $b_5 = 0.3342$, $b_6 = -0.1244$, $b_7 = -0.1009$, $a_1 = -0.8662$, $a_2 = -2.746$, $a_3 = 2.339$, $a_4 = 2.507$, $a_5 = -2.095$, $a_6 = -0.7602$ and $a_7 = 0.6211$. Therefore, the resulting total fractional order controller is an 8th-order digital IIR filter given by:

$$C_T(z) = 0.09 + 0.025\left(\frac{1-z^{-1}}{T_s}\right)R_T(z).$$

- Brake controller:

$$R_B(z) = \frac{\sum_{k=0}^{7} b_k z^{-k}}{1 + \sum_{k=1}^{7} a_k z^{-k}}, \qquad (13)$$

  with $b_0 = 0.3529$, $b_1 = 0.1878$, $b_2 = -1.0274$, $b_3 = -0.5381$, $b_4 = 0.9959$, $b_5 = 0.5128$, $b_6 = -0.3215$, $b_7 = -0.1625$, $a_1 = -0.5400$, $a_2 = -2.88062$, $a_3 = 1.5053$, $a_4 = 2.7658$, $a_5 = -1.3952$, $a_6 = -0.8852$ and $a_7 = 0.4299$. In this case, the resulting total fractional order controller is an 8th-order digital IIR filter given by:

$$C_B(z) = 0.07 + 0.11\left(\frac{1-z^{-1}}{T_s}\right)R_B(z).$$

III. Adaptive Cruise Control

Adaptive Cruise Control (ACC) technology improves upon the function of standard cruise control by automatically adjusting the vehicle speed and distance to that of a target vehicle. ACC automatically decelerates or accelerates the vehicle according to the desired speed and distance settings established by the driver. If the subject vehicle cannot detect

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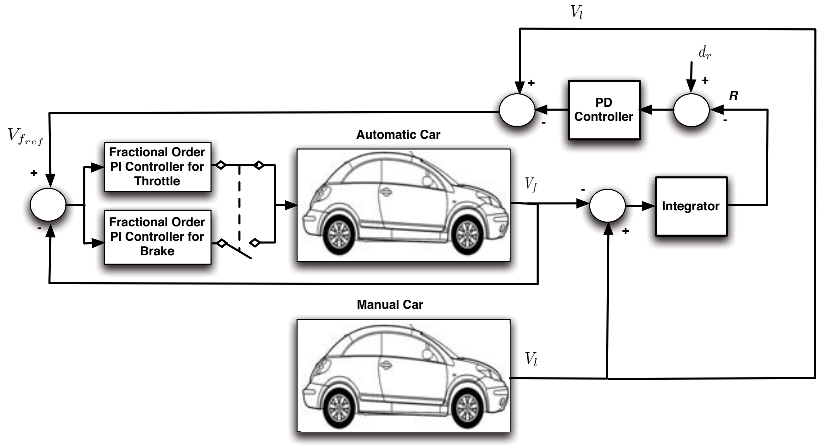

Fig. 4: Block diagram of ACC system

a leading car in the same lane traveling slower than its desired speed, that is not in a following mode and needs only track a desired speed. Thus, at least two control law regimes are needed: one for a desired velocity tracking -it was called CC mode in Section II); and another one which tracks a desired following distance between the subject vehicle and a detected lead vehicle. Fig. 4 shows a scheme the ACC.

A. Reference Inter-distance

In ACC, the aim is to set the distance between two cars (inter-distance) in a safe distance. Therefore, it is necessary to define the safe inter-distance. During the last decades the well known safe inter-distance has been calculated as a minimal distance to avoid a collision if the preceding vehicle were to act unpredictably. In fact, the safe inter-distance is calculated from the Newtonian motion equation, permitting to obtain the necessary distance to full stop without collision, where the safe distance, d_r can be computed using the following equation, which is known as constant-time headway policy [10]:

$$d_r = hV + d_c + l, \tag{14}$$

where l is the vehicle length, d_c is the additional distance between two vehicle in order to avoid collision, V is vehicle velocity and h is constant-time headway which is specified by the driver. There are many possible control strategies for vehicle following in a convoy, depending on the information about the motion of other vehicles which is used. For example, the controller may take account only of the vehicle immediately ahead, or of several preceding vehicles, or of those both ahead and astern, or of the platoon leader and possibly others. Different strategies to obtain the safe inter-distance have been used in the literature. Here we will use the one proposed in [11]. Specifically, the acceleration will be assumed to satisfy a bound

$$|\dot{V}| \leq \gamma_{max}, \tag{15}$$

which is taken to represent the worst case scenario in an emergency, while the jerk is required to be bounded by

$$|\ddot{V}| \leq J_{max}, \tag{16}$$

arising from limitations on the response of the traction and braking systems in the vehicle, as well as what is physiologically tolerable for the occupants. Regarding to [11], no collision can occur if the following condition is satisfied:

$$h \geq \frac{2\gamma_{max}}{J_{max}}. \tag{17}$$

Once the reference safe inter-distance has been generated, the PD controller will seek to ensure that d_r is tracked as closely as possible.

B. Design and Tuning the Distance Controller

In this section, a PD controller will be designed in order to perform reference speed for the following car and guarantee the tracking of the reference inter-distance. In order to design and tune the controller a range R is defined:

$$\dot{R} = V_l - V_f, \tag{18}$$

where R can represent the real inter-distance when initial value of (18) is initial value of inter-distance d. Fig. 5 shows the closed loop block diagram of the system. As it can be seen, the outer loop system can be simplified as:

$$F(s) = C_d(s)G_c(s)G_d(s),$$

where $C_d(s) = k_{p_2} + k_d s$ is a classical PD controller. And

$$G_c(s) = \frac{C(s)G(s)}{1 + C(s)G(s)}$$
$$G_d(s) = \frac{1}{s}.$$

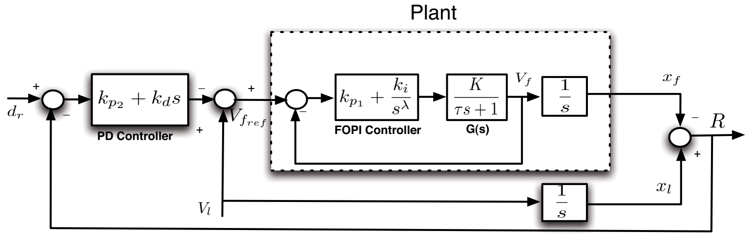

Fig. 5: Scheme of the closed loop system

As aforementioned, there are two inner-loop system regarding to the brake and throttle control. In order to design a unique PD which will be applicable for both systems, we will tune the parameter based the system with lower phase margin (throttle controlled system). The aim is to tune the PD to obtain $\phi_m > 80$deg. Considering throttle system and following specifications:

$$Arg\left(F(j\omega_{cp})\right) = -\pi + \phi_m, \tag{19}$$

$$\left|F(j\omega_{cp})\right| = 0dB, \tag{20}$$

Thereupon, the controller parameters i.e. k_{p_2} and k_d are obtained as 0.7 and 1.2, respectively. Bode plots for both closed loop systems, i.e. brake and throttle, are depicted in Fig. 6. As can be seen, both system met the specified phase margin, i.e. $\phi_m > 80$deg. The controlled system when the throttle is activated will obtain the $\phi_m = 86$deg where the brake controlled system will reach to $\phi_m = 81$deg.

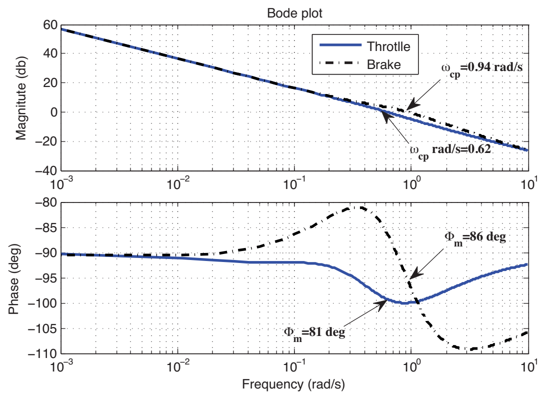

Fig. 6: Bode plot of the controlled system

IV. Simulation and Experimental Results

The controlled system has been tested in simulation and experiments in a private driving circuit illustrated in Fig. 7. This circuit (located at the Centre for Automation and Robotics) has been designed with scientific purposes so only experimental vehicles are driven in this area. It includes 90deg bends and different slopes so as to validate the controller in different circumstances as close to a real environment as possible.

Fig. 7: Private driving circuit at the Centre for Automation and Robotics

Two vehicles were used for the experimental phase: a fully-automated vehicle and a manually driven one (see Fig. 8). The former is a convertible Citroën C3 Pluriel. The car is equipped with automatic driving capabilities with hardware modifications made to the throttle and the brake pedal actions. The latter vehicle is an electric Citroën Berlingo van, also equipped with automatic driving capabilities. For the purpose of this work, it was driven by a human driver making the leading cars behavior as close to a real traffic situation as possible.

With respect to the automation process, the Pluriel's throttle is controlled by an analogue signal that represents the pressure on the pedal, generated with an analogue card [12]. For the brake, an electro-hydraulic braking system is mounted in parallel with the original one [13], and is controlled via an I/O digital-analogue CAN card.

Both vehicles are equipped with real time kinematic differential global positioning systems (RTK-DGPS) working at 5Hz as the main sensor. This sensor is used to acquire driving information, providing 1-centimetre precision. An inertial measurement unit (IMU) is installed in the convertible car to provide positioning in case of GPS receiver failure [14]. A personal computer memory card international association (PCMCIA) proxim wireless combocard is installed in the PC of each car, and a central station is used to send the relevant information from the leading to the trailing car [15]. The trailing vehicle is equipped with an industrial on-board PC that is in charge of receiving the information coming from the wireless communication system and the sensorial inputs,

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and of sending the output generated to the actuators in each control cycle (200ms).

Fig. 8: Commercial prototype vehicles used for the experimental phase

A. Cruise Control Results

The simulation results are carried out using the MATLAB/Simulink environment. In order to show the efficiency of the robust controller, a random noise with mean value of 0.85 is added to nominal value of $\tau = 2.25$. Firstly, in order to see the brake action and the performance of the robust controller which is designed for uncertain system (2), the car moved with fixed pedal to reach the velocity of 30km/h, then the brake controller is activated. The experimental brake results are illustrated in Fig. 9. As mentioned before, the main important limitation which have been considered is acceleration i.e. $[-2, 2]$. Regarding to these results, it is obvious that the controlled system fulfils the acceleration limitation.

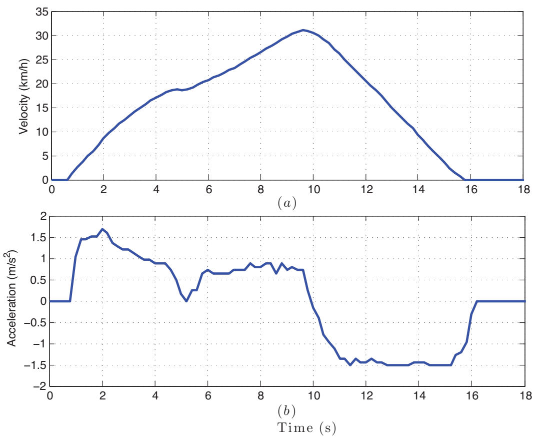

Fig. 9: Brake control results

Fig. 10 shows the simulation and experimental results of the hybrid controlled system with two different references for speed. Velocity tracking, acceleration and normalized control action are shown in this figure. As it can be seen, the results show that the acceleration and control action are into the desired intervals. One can appreciate the soft action over vehicle's actuators obtaining a good comfort for car's occupants-this is reflected in the acceleration values. Moreover, the experimental results are in agreement with the simulations.

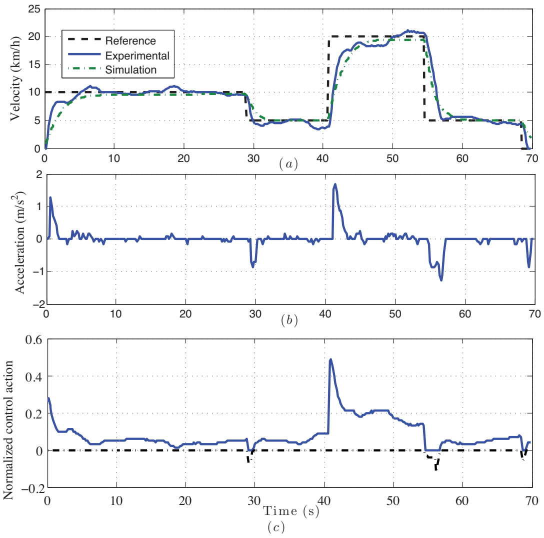

Fig. 10: Cruise control results

B. ACC Results

The distance between vehicles at the beginning of the test was set at 6 meters. Once this distance was achieved with 1-centimetre accuracy using the RTK-DGPS positioning system, the test was initiated. The inter-distance dynamic model is parameterized to provide a maximum speed $V_{max} =$ 50km/h, a maximum acceleration $\gamma_{max} = 2$m/s^2, a maximum jerk $J_{max} = 5$m/s^3. Regarding to γ_{max}, J_{max} and (14), headway constant time is set as $h = 0.8$s.

The simulation and experimental results of ACC are shown in Fig. 11. The results related corresponds to $d_c + l = 9.6$m. The top depicts the simulated and experimented follower vehicle's speed with respect to the leading one. The second shows the desired inter-distance and the values obtained using the proposed fractional order controllers. The third and fourth plots show the acceleration and Jerk, respectively. Moreover, normalized control action is shown at the bottom. During all the time interval the inter-distance is tracking the reference inter-distance and velocity of leader and follower are significantly close to each-other. As it can be seen, during both acceleration and deceleration the system behave efficiently which is verifying the performance of the hybrid fractional order controller. The leading car reduces its speed significantly at time 64s, and the following car properly follow the reference inter-distance as well as the time it increases the speed which also verify the designed controller. Concerning the acceleration and jerk, all three controllers satisfied the initial pre-requisites- $\gamma_{max} = 2$m/s^2, $J_{max} = 5$m/s^3.

V. CONCLUSION

A hybrid fractional strategy is proposed to control throttle and brake in adaptive cruise control application. As the system has different dynamics during the acceleration and deceleration of the car, different controllers are needed. A fractional order PI is used to control the throttle action, whereas a robust fractional order PI controller is designed for the uncertain model identified regarding to different brake actions. Based on this system, an ACC is applied to control the safe distance between two cars. A PD controller is designed to obtain this goal. The controllers are simulated and then tested experimentally. Both simulated and experimental results show the efficiency of the proposed strategy.

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