Research Article
A Robust Longitudinal Control Strategy for Safer and Comfortable Automotive Driving

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Abstract: A reference model based control approach for automotive longitudinal control is proposed in this study. The reference model is nonlinear and provides dynamic solutions consistent with safety constraints and comfort specifications. Moreover, a design procedure of Adaptive Cruise Control (ACC) and stop-and-go control systems is provided which deals with the electric car following various scenarios in urban environment. Since many vehicle/road interaction factors (such as road slope, aerodynamic forces) and actuator dynamics are very poorly known, a robust fuzzy logic based control strategy is further proposed in this study. A set of simulation results showing the suitability of the proposed technique for various demanding scenarios is also included in this study.

Keywords: Adaptive cruise control, electric car technology, longitudinal control, stop-and-go control, stop and go maneuvers

INTRODUCTION

Traffic accidents have become social trouble along with the increase in drivers and diversification. In traffic accidents the rear-end collision includes the risk of severe injury. This problem can be significantly improved by optimizing the inter-vehicle distance.

Adaptive Cruise Control (ACC) and stop-and-go control systems have been thoroughly studied in recent years (Goodazi and Esmailzadeh, 2007), Some of such research papers may be examples of problems relating to longitudinal control. Some others may concern the inter-distance control in highways where the vehicle velocity remains mainly constant. Where as others may deal with the vehicle circulating in towns with frequent stops and accelerations. In all situations, safety and comfort are often the main goals but most often oppose each other (Vahidi and Eskandarian, 2003).

The present paper focuses on the integration of the in-wheel electric motors into the conception and control of road vehicles. The novelty of the present work is that the in-wheel electric motor is considered to be the only control actuator signal in acceleration and deceleration phases, simplifying the architecture of the design of the vehicle and of the control laws. A recall the dynamic inter-distance model for generating a reference distance between the leader and follower car was introduced in this study (Martinez and de Wit, 2007).

The main contribution of this study consists in finding a fuzzy control algorithm that leads to the expected reference speeds and acceleration of the backward vehicle, while keeping a reference distance with the vehicle in front. Moreover, the control law will have to be robust to a disturbance-road inclination, aerodynamic forces or rolling resistance.

METHODOLOGY

Model and dynamic representation of the vehicle: Since the main goal of the analysis consists in achieving only longitudinal control of the vehicle, then the full model can easily be taken as a bicycle model, (Goodrich and Boer, 2000), as shown in Fig. 1. Here, G_s and G_u are respectively the centers of gravity of the suspended and unsuspended mass, L_f and L_r are the distances from the center of mass to the front and rear axle. The suspension dynamics are taken into account, with the associated load transfer that arises when the vehicle is accelerating or decelerating. The forces that act on each axle are shown in Fig. 1. The overall system equations including the vehicle, wheel and load transfer dynamics are given as follows (Hartani *et al*., 2010; Sekour *et al*., 2013):

$$M_v \dot{V}_x = \sum_{i=1}^{2} F_{x_i} - F_{res}$$

$$F_{res} = F_{aero} + F_{roll} + F_{slope}$$

$$\begin{cases} F_{roll} = C_{rr} M_v g \\ F_{slope} = M_v g \sin(\alpha_p) \\ F_{aero} = C_x V_x^2 sign(V_x) \end{cases}$$

$$F_{x_i} = \mu_{x_i}(S_{x_i}) N_i$$

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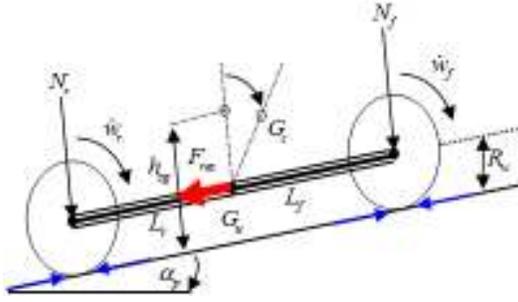
Fig. 1: Bicycle analogy of the vehicle model

Table 1: Electric vehicle parameters

C_{rr}	0.010	L_r	1.421 (m)
M_v	1662 (kg)	h_{cg}	0.500 (m)
g	9.810 (m/sec^2)	L	L_f+L_r (m)
C_x	0.306	α_p	0.020 (rad)
R_w	0.294 (m)	μ_p	0.800
L_f	1.104 (m)	S_p	0.200
J_v	2630 (kg*m^2)	J_w	1.284 (kg*m^2)

$$S_{x_i} = \begin{cases} (w_i R_{w_i} - V_x)/w_i R_{w_i} & w_i R_{w_i} > V_x \\ (w_i R_{w_i} - V_x)/V_x & w_i R_{w_i} < V_x \end{cases} \quad (1)$$

$$\begin{cases} N_f = \dfrac{gM_v}{2}\left(\dfrac{L_r}{L} - \dfrac{h_{cg}}{gL}\dot{V}_x \alpha_p - \dfrac{h_{cg}}{L}\alpha_p \right) \\ N_r = \dfrac{gM_v}{2}\left(\dfrac{L_f}{L} - \dfrac{h_{cg}}{gL}\dot{V}_x \alpha_p - \dfrac{h_{cg}}{L}\alpha_p \right) \end{cases}$$

Moreover,

R_w = The wheel radius

F_{aero} = The aerodynamic drag force

$N_{f/r}$ = The normal force on the tire

F_{x_i} = The longitudinal tire force

μ_x = The longitudinal friction

w_i = The wheel angular speed

F_{roll} = The rolling resistance force rolling

F_{slope} = The force due to the slope of the road

L_i = The distance from the center of gravity to the axle and the index $i = f$; r with the signification: f = front, r = rear, the values of the above parameters are described in Table 1

The function Kachroo will be used to change the parameter μ_x, $\mu_x(S_x) = (2\mu_p S_p S_x / \mu_p^2 + S_x^2)$ which is related by a non-linear function to the wheel slip S_x, whether motive or curbed and where μ_p and S_p are the peak values. This function gives values compatible with experimental data given in Widmer and Le Solliec (2010), especially in the range $S_x \in [0 \quad 0.3]$.

Dynamic inter-distance generation: The inter-distance reference model describes a virtual vehicle dynamics which is positioned at a distance d_r (the reference distance) from the leader vehicle. The reference model's dynamics are given by:

$$\ddot{d}r = \ddot{x}_l - \ddot{x}_{fr} \quad (2)$$

$$\ddot{x}_{fr} = u_r(dr, \dot{dr}) \quad (3)$$

where,

$\ddot{x}_l$ = The front vehicle acceleration

$\ddot{x}_{fr}$ = The following vehicle's acceleration, which is a nonlinear function of the inter-distance and its time derivative

Introducing $\tilde{d} = d_0 - dr$ in formula (3), where d_0 is the safe nominal inter-distance, the control problem would be then to find a suitable feed-forward control u_r, when $\tilde{d} > 0$, such that all the solutions of the dynamics (2) fulfill the following comfort and safety constraints:

- $dr \geq d_c$, with d_c the minimal inter-distance
- $\|\ddot{x}_r\| \leq \gamma_{max}$, where γ_{max} is the maximum attainable longitudinal acceleration
- $\|\dddot{x}_r\| \leq J_{max}$, with J_{max} a bound on the driver desired jerk

In Wong (1978), the authors proposed to use a nonlinear damper/spring model $u_r = -c|\tilde{d}|\dot{\tilde{d}}$, which can be introduced in the dynamics of formula (2) to give:

$$\ddot{\tilde{d}} = -c|\tilde{d}|\dot{\tilde{d}} - \ddot{x}_l$$

The previous equation may be analytically integrated and expressed backwards in terms of d_r as follow (Fig. 2):

$$\dot{d}_r = \frac{c}{2}(d_0 - d_r)^2 + \dot{x}_l(t) - \beta$$

$$\beta = \dot{x}_{fr}(0) + \frac{c}{2}(d_0 - d_r(0))^2 \quad (4)$$

Note that this reference inter-distance depends upon the leading vehicle, distance d_0 and parameter c, which is, in turn, an algebraic function of safe and comfort parameters d_c, V_{max}, γ_{max} and J_{max}:
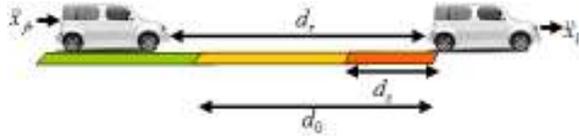
Fig. 2: The inter-distance reference model

Fig. 3: Proposed simulation model

$$d_0 = \sqrt{\left(\frac{16}{27}\right)\frac{V_{max}^2}{\beta_{max}} + d_c} \qquad c = \frac{27\beta_{max}^2}{8V_{max}^3}$$

$$\left|\ddot{x}_f^r(t)\right| \le \max\left\{\frac{27}{8}\frac{V_{max}^2}{\beta_{max}}, 2.6\frac{V_{max}}{\beta_{max}}\gamma\right\}$$

Finally, the feed-forward control law-or the follower acceleration-yields from (3):

$$\ddot{x}_{f_r} = u_r = -c\left|d_0 - d_r\right|\dot{d}_r \qquad (5)$$

where, the inter-distance evolution comes from the numerical integration of (5).

FUZZY CONTROLLER

This section proposes a fuzzy logic algorithm to control the host vehicle. The distance and the relative velocity between the host vehicles are the inputs of the fuzzy controller. Fuzzy controller is suitable for multi-parameters and nonlinear control problems and the system transfer function is not required.

In this study, Mamdani's Fuzzy Inference method (FIS) is applied. The singleton membership function of the outputs is used. This type of output membership function makes it convenient for the defuzzification process because it simplifies the computational efforts compared with other types of membership function. The entire fuzzy system is developed and implemented by using MATLAB. Figure 3, show the block diagram of the fuzzy controller. The two input variables are the "relative velocity" and the "distance error" The block in the middle represents all the fuzzy inference rules which are the control strategy of the proposed system. The output variables are used for the control of the brake and velocity.

Each linguistic variable contains seven terms. The meanings of each input variable are as follows:

NL : Negative Large
NM : Negative Medium
NS : Negative Small
PS : Positive small
PM : Positive medium
PL : Positive large
Z   : Zero

The outputs are divided into two sides, the negative one which represents the braking command and the

(a)

(b)

(c)

Fig. 4: Membership functions, (a) distance error, (b) relative velocity, (c) output command

positive side which represents the velocity ratio command (Fig. 4 and 5):

Table 2: The fuzzy rule of output command

Output		Distance error						
		NL	NM	NS	Z	PS	PM	PL
Relative velocity	NL	NVL	NVL	NL	NM	NM	NS	NS
	NM	NVL	NL	NM	NM	NS	NS	Z
	NS	NL	NM	NS	NS	NS	Z	Z
	Z	NM	NS	Z	NS	Z	PS	PS
	PS	NM	Z	Z	Z	Z	PM	PL
	PM	NS	Z	Z	PS	PM	PL	PVL
	PL	NVL	NVL	NL	NM	NM	NS	NS

Fig. 5: Surface

Fig. 6: Motors rotation for leading and follower cars
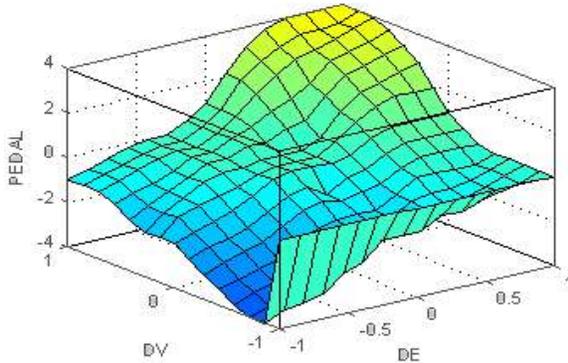
NVL : Negative very large
NL : Negative large
NM : Negative medium
NS : Negative small
PS : Positive small
PM : Positive medium
PL : Positive large
PVL : Positive very large
Z : Zero

The fuzzy control rules play an important role in fuzzy control and also provide a short description of the behavior of human conduct, so it is significant to establish the fuzzy rules in the fuzzy control system (Table 2).

RESULTS AND DISCUSSION

The leading and follower cars will be initially running at different speed, $\dot{x}_l(0) = 9\,m/sec$ and $\dot{x}_f(0) = 5\,m/sec$. Besides, the inter-distance dynamic model is parameterized to provide a maximum speed $V_{max} = 30$ m/sec^2, a maximum acceleration $B_{max} = 7$ m/sec^2 and a minimum inter-distance $d_c = 5$ m. The slope angle $\alpha_p = 0.01\,rad$ at ($t = 50$ sec).

A car-following with a change in the preceding vehicle velocity (Fig. 6 to 14): When the follower vehicle comes near to the leading vehicle, the velocity is adapted with comfortable deceleration and the reference vehicle is positioned at a safe distance.
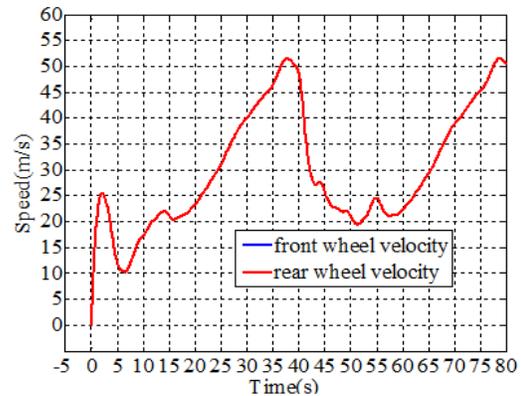
Fig. 7: Velocities for leading and follower cars

Fig. 8: Relative velocity between leading and follower cars

A stop-and-go scenario (Fig. 15 to 23): At (20 and 40 sec) and (70 and 80 sec) the leading vehicle is
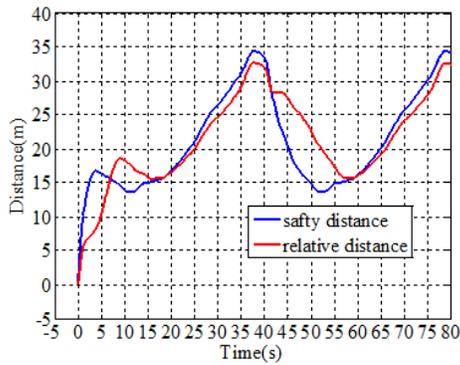
Fig. 9: Safety distance, relative distance

Fig. 10: Distance error
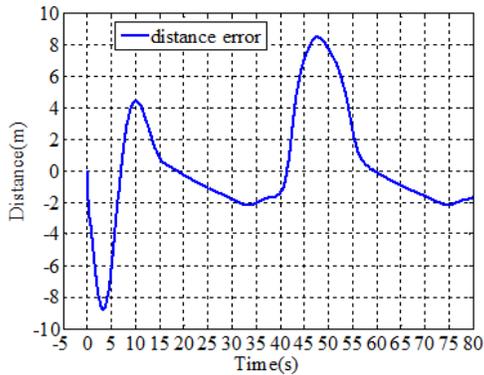

Fig. 11: Accelerations for leading and follower cars

Fig. 12: Jerks for leading and follower cars

Fig. 13: Motor torques

Fig. 14: Load torques

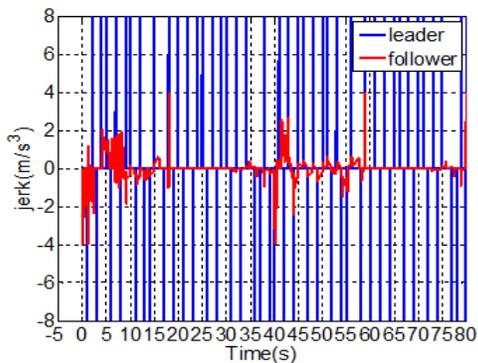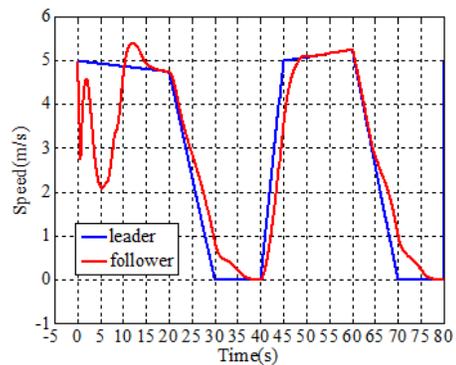Fig. 15: Motors rotation for leading and follower cars

Fig. 16: Velocities for leading and follower cars
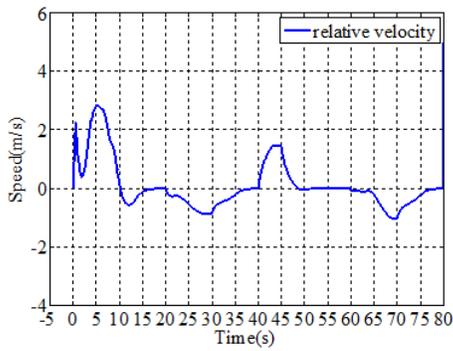
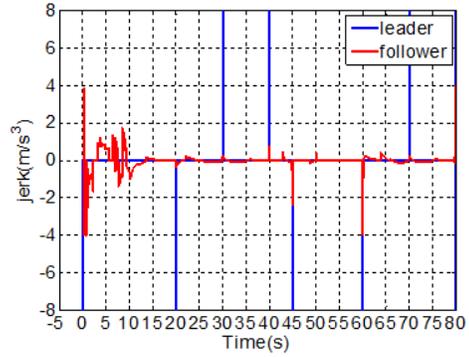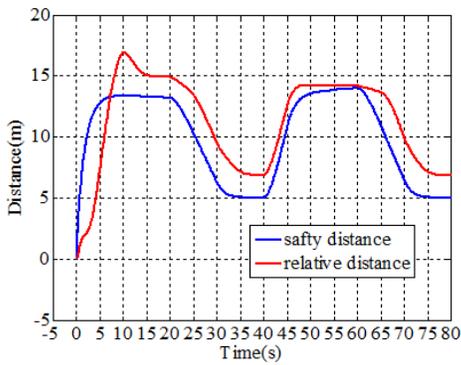Fig. 17: Relative velocity between leading and follower cars
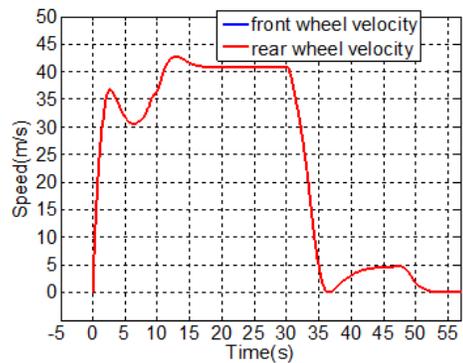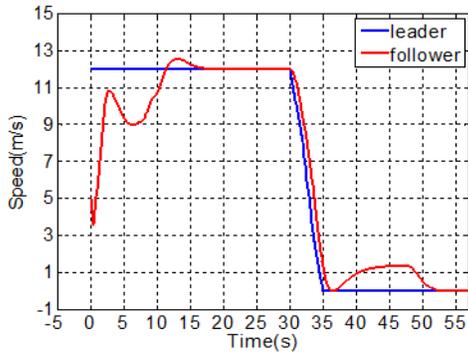

Fig. 18: Safety distance, relative distance

Fig. 19: Distance error

Fig. 20: Accelerations for leading and follower cars

Fig. 21: Jerks for leading and follower cars

Fig. 22: Motor torques

Fig. 23: Load torques

Fig. 24: Motors rotation for leading and follower cars

Fig. 25: Velocities for leading and follower cars

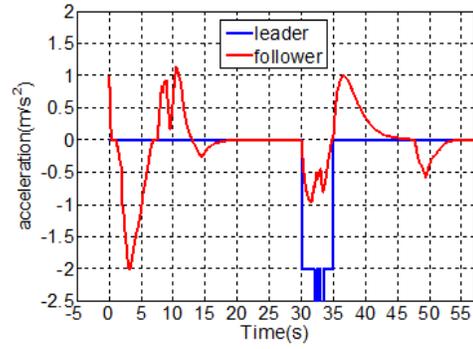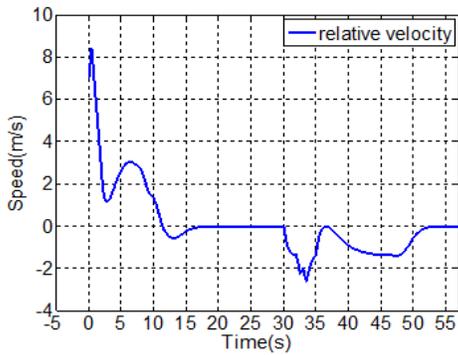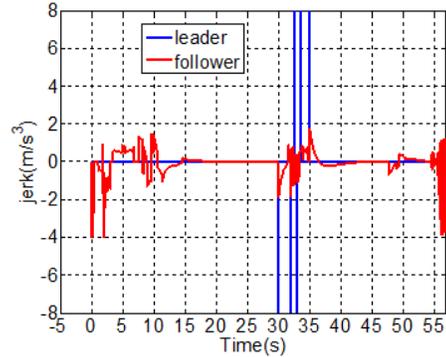Fig. 26: Relative velocity between leading and follower cars

Fig. 27: Safety distance, relative distance

Fig. 28: Distance error

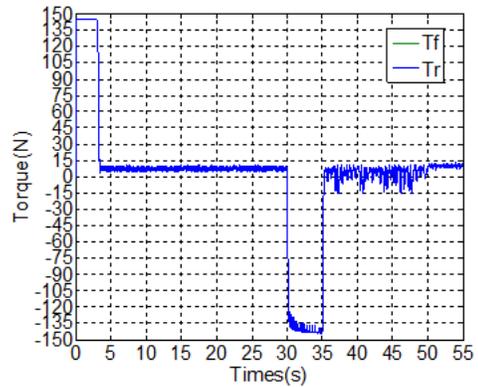Fig. 29: Accelerations for leading and follower cars
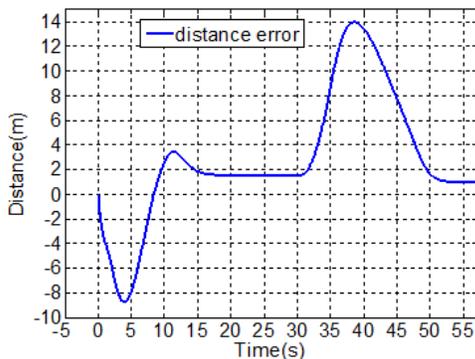
Fig. 30: Jerks for leading and follower cars
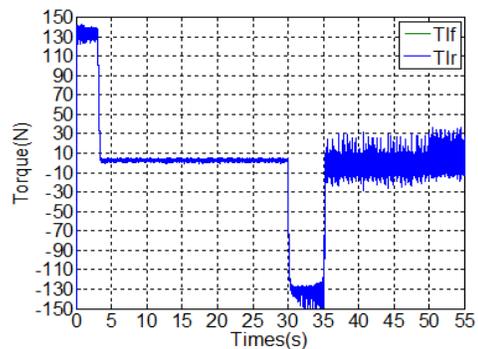
Fig. 31: Motor torques

Fig. 32: Load torques

accelerated and decelerated (stop-and-go) with a usual acceleration value but high jerk; however, the following vehicle is maintained to a safe distance and with bounded jerk.

A car-following with hard stop scenario (Fig. 24 to 32): At t = 30 sec the leading vehicle stops with a high braking value while the follower vehicle comes to a complete stop before the critical distance d_c = 5 m with lower braking.

CONCLUSION

In this study, a reference model based control approach for longitudinal control for an electric vehicle has been presented. The proposed structure combines a reference model in which the former will be to verify the safety and comfort constraints, while the latter will be in charge of the model-tracking. In this study, the distance controller uses fuzzy algorithm in which the inputs are the distance and relative velocity whereas the outputs from the controller are separated into two groups. The first one is the command to accelerate the vehicle and the other output is the command to decelerate the vehicle in case of braking command. The simulation results included in this study show that the ACC system which is developed for the AIT intelligent vehicle is able not only to control the vehicle to run at a desired velocity when operated in velocity control mode but also maintain efficiently the distance between the host vehicle and the obstacle vehicle.

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