Adaptive Cruise Control optimized for multi-objective

Salvador N. Obama Oyana; Jun Li

Department of Automation, University of Science and Technology of China, Hefei,230026

E-mail: pucho@mail.ustc.edu.cn
E-mail: ljun@ustc.edu.cn

Abstract: With the great objective of improving the adaptive cruise control (ACC) system, in terms of safety between the vehicles that travel the route, both the ego car and the lead car, energy-saving, and driver comfort, we analyze these terms as restrictions system control for them, we analyze our system from the driving data of a real vehicle. A hierarchical control architecture is adopted, and the top controller is designed based on Model Predictive Control (MPC). The numerical simulation shows that the proposed MPC controller considerably reduces the energy consumption of the ACC system if we compare it with the energy consumption in cruise control (CC) system and the comfort under the premise of guaranteeing the performance and the inter-vehicular distance between the two vehicles is also quite stable.

Key Words: Adaptive Cruise control, multi-objective control, Model predictive control

1 INTRODUCTION

The Adaptive Cruise Control (ACC) system is just an upgrade to the Cruise Control (CC) system, which acts on the throttle to maintain the speed set by the driver. In the ACC, a radar is added, which calculates the distance between vehicles and gives the system a limited braking capacity, so that, if there is a car in front of a certain distance, the system will change from speed control to cruise control.

ACC, therefore, adapts to different traffic conditions, preventing the driver from having to reactivate the system every time he feels forced to brake, as is the case with CC. Thanks to these operational features, ACC is already considered an indispensable tool in future generations of smart cars. Currently, there are already numerous vehicles equipped with this system. Mitsubishi was the first car manufacturer to use this system, but its technology at that time was based on laser technology and, unlike current systems, it did not act on the brake, but only on the accelerator.

Taking into account that for the activation of the ACC the driver must specify the desired speed and safety distance instructions; and these can be modified later in operation. In addition, the limitations of the specific desirable behavior should be taken into consideration. Due to the need for restrictions, several traditional controllers such as the PID are not so effective. With a little more advanced controller such as the LQR, slower responses can be obtained on our system compared to MPC[1] . The MPC is ideal for applying in ACC systems; because it has proven to overcome with quite an efficiency and solvency complex control problems of multiple restricted variables.

The greatest strength of the MPC is its online system optimization, stability and viability. Therefore, the advantage of MPC for ACC is that a high degree of control performance can be achieved[1].

Currently most or almost all vehicles currently produced are equipped with the ACC system. The first brand to introduce the ACC system was Mitsubishi, whose system was based on laser technology and, unlike today's systems, it did not act on the brake, but rather ´Only on the accelerator and the gear change. Today, manufacturers such as Audi, BMW, Jaguar or Mercedes-Benz (among others) provide some of them. Bearing in mind that to activate the ACC the driver must specify the desired speed and safety distance instructions, and that these can be modified later in operation

In this article we try to adjust to the driver's habits and concerns, such as car performance, inter-vehicle distance, energy saving and passenger comfort, the ACC goal of our work is to make the control response closer to feasibility and actual conditions. That can prevent collisions and maintain a safe distance with the leading car as the main objective and comfort and energy consumption as minor objectives simultaneously.

2 RELATED WORK

Paper [2]implements an MPC approach in a basic ACC system. The objective of his model is to maintain both the ego car and the lead car at a constant speed, using an MPC controller, he manages to achieve the required stability with the specified input restrictions and the target speed for a constant speed of the preceding vehicle. In [3] focuses on exploring the potential of reset control in situations where the vehicle driver decides to increase the safety distance. It is considered that this setpoint change will be made when the ACC system is working in follower mode and in a stationary state, that is, the car under study maintains the predefined safety distance with respect to the car in front and both circulate at constant speed. Due to the fact that our interest is focused on control, a simple scenario with ideal sensors has been considered, in which only longitudinal movement is considered in order to facilitate understanding.

The increase in research and testing of additional control algorithms for the perfect complementation with the ACC system has skyrocketed in the last decade along with the growth of new artificial intelligence algorithms and the construction of fully autonomous vehicles. [4] Develops an ACC system based on eco-driving for two typical scenes of traffic following the car. The implemented ACC system is also given by MPC to obtain objectives of ecological driving, driving safety, comfort， and monitoring capacity. address the issue of driving safety, which they guarantee by restricting the space between the two vehicles. They also compare the performance of the MPC-based ACC they propose with the PID controller-based ACC in two different environments, arriving at the conclusion that the model they propose is more stable, and offers more safety to passengers than the model based on PID.

In recent years there have also been investigations of the ACC system with a nonlinear model predictive control； or a modified MPC model. Authors implementing an ACC with a two-loop NMPC control: an outer loop to maintain a safe distance from the vehicle in front and an inner loop to control the brake pedal and throttle opening position are in common use. [5] proposes a different approach in which a single control loop is used. In this research addressed the objective of distance tracking as an addition to the Predictive Control of the nonlinear model by extending the LTI models obtained by linearizing the nonlinear dynamic model of the vehicle, the response obtained from the proposed system offers a smooth variation in the signal of throttle and brake control which subsequently results in smoother acceleration of the vehicle. [6]presents a plug-in hybrid electric vehicle, with two energy sources. in it analyzes an ecological adaptive cruise controller (Eco-ACC) that considerably improves both the reduction of energy consumption and the safety of the vehicle. [7]He demonstrates that the use of an Eco-ACC system considerably improves total energy costs and vehicle safety. For this he uses a nonlinear model predictive control technique, he uses this nonlinear controller for the good optimization of the vehicle speed.

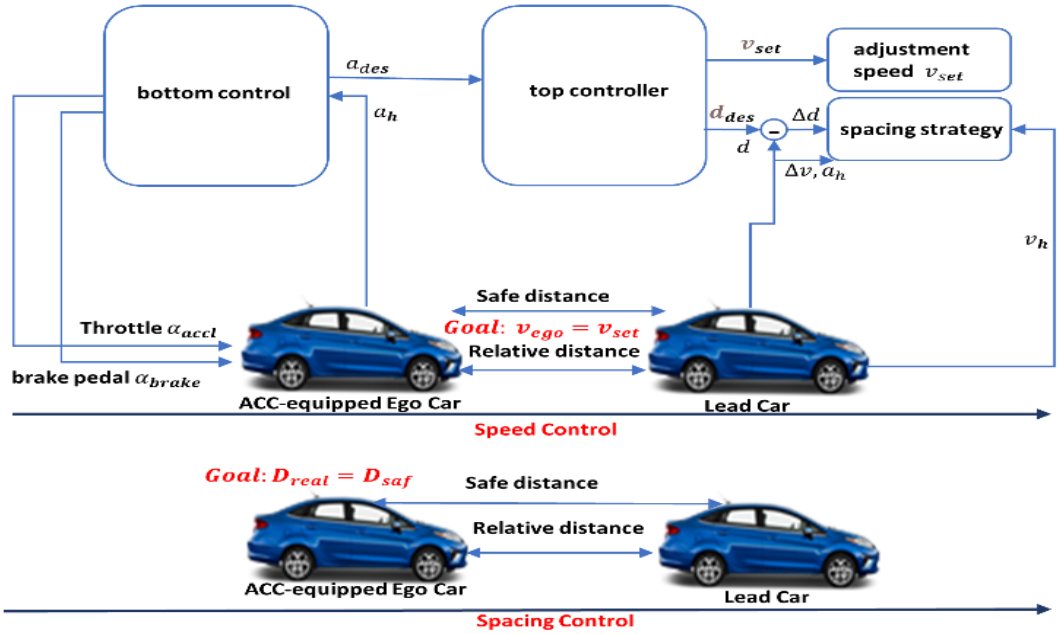


Figure 1: Control block diagram for ACC

3 VEHICLE MODEL

We use a real vehicle for the acquisition of information for the modeling of our system. Information on the lateral dynamics of the vehicle, driver control, and information on the driving status of the ego car.

To remove the influence of time delay, a first-order delay inertial link is introduced, whose input and output are the expected acceleration a_{des} and the actual acceleration a_h, respectively. Its transfer function has the form:

$$a_f = \frac{k_s}{T_g s + 1} d_{des} \tag{1}$$

Where, $k_s = \mathbf{1}$ is the system gain, $T_g = 0.4$ is the time constant, in this article, $d_{des} = t_v v, + d_0,$

$$t_g = \begin{cases} 2.4 & v < 3m/s \\ 1.5 & v > 20m/s \end{cases} \tag{2}$$

According to the longitudinal kinematics of the real vehicle model that we use, the following two state variables are defined:

$$\begin{cases} \Delta d = d - d_{des} \\ \Delta v = v_f - v_h \end{cases} \tag{3}$$

d is the actual distance between vehicles, v_f is the actual speed of the target vehicle, and v_h is the speed of the host vehicle. The state equation is used to describe the longitudinal dynamics model of the vehicle, and its state variables are as follows:

$$x = [\Delta d \quad \Delta v \quad a_h]^T \tag{4}$$

the dynamic model will be the following:

$$\begin{cases} \Delta d = 2a.v_f \cdot a_f + b \cdot a_f - \Delta V - \Delta \dot{v} \cdot a_P T \\ \Delta \dot{v} = a_P - a_f \\ \dot{a}_t = k_s a_{des} / T_g - a_f / T_g \end{cases} \tag{5}$$

In the formula, a_P it is the acceleration of the preceding vehicle; T is the sampling step $x = \left[\Delta d, \ \Delta v, \ a_f\right]^T$ control variable, $u = a_{des}$, perturbation $\eta = p$, since the Construction of a model of generalized longitudinal dynamics would be.

$$\dot{x} = Ax + Bu + G\eta \tag{6}$$

each matrix of coefficients satisfies:

$$A = \begin{bmatrix} 0 & -1 & 2av_f + b + T \\ 0 & 0 & -1 \\ 0 & 0 & -1 / T_g \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} 0 & 0 & K_s / T_g \end{bmatrix}^T \tag{8}$$

$$G = [-T \quad 1]^T \tag{9}$$

We linearize and discretize formula (5):

$$x(k+1) = A_t x(k) + B_t u(k) + G_t v(k) \tag{10}$$

$$A_t = I + AT, \ B_t = BT, \ G_t = GT_0 \tag{11}$$

We take the output of the system as $y = \left[\Delta d, \ \Delta v, \ a_f\right]^T$, The output equation of the system:

$y = cx$, the output coefficient matrix $C = I_{3\times3}$

3.1 Control Objective Analysis.

3.1.1 Energy consumption

According to the literature [7], it can be known that the acceleration of the vehicle itself and the output control variables of the system are controlled to improve and save fuel consumption (energy) of the vehicle, the form is as follows:

$$\begin{cases} a_{min} < a_h(k) < a_{max} \\ u_{min} < u(k) < u_{max} \end{cases} \tag{12}$$

Where, $a_{min} = 2m/s^2$, $a_{max} = 1.4m/s^2$, $U_{min} = -3m/s^2$, $U_{max} = 2m/s^2$ are the upper and lower limits of acceleration and the control variable, respectively.

3.1.2 driver comfort

In order to improve driving comfort, the shaking b of the vehicle and the rate of change Δu of the control variable should be reduced and limited, its form is as follows:

$$\begin{cases} b_{min} < b(k) < b_{max} \\ \Delta u_{min} < \Delta u(k) < \Delta u_{max} \end{cases} \tag{13}$$

Where, $b_{min} = -4m/s^3$, $b_{max} = 4m/s^3$, $\Delta u_{min} = = -1{,}5m/s^3$, $\Delta u_{max} = = 1{,}5m/s^3$

are the upper and lower limits of the vehicle jerks and the rate of change of the control variables respectively.

3.1.3 Inter-vehicle distance

Considering that the space between the two vehicles is too small, the vehicle needs emergency braking, at this time the braking force is constant for the ABS

system to provide the maximum braking force, and the brake deceleration in the process of increasing in braking force is linear, the braking process satisfies the following relationships.

$$D_{real} = D_{safe} + T_g \, x \, v_{ego} \tag{14}$$

$$V = min\left[V_{Lead\ car,}\ V_{ego\ car}\right] \tag{15}$$

$$\int_0^{T_3} \frac{1}{\delta M}\left(F_{ABS}\cos\theta + G\sin\theta + \frac{C_D A v^2}{21}\right)dt = (v_{ego} - \frac{F_A T_2}{2M\delta}) - v_{lead\ car} \tag{16}$$

$$\int_0^{T_3} v\,dt = d + v_{ego\ car}(T_1 + T_2 + T_3) \tag{17}$$

Where F_{ABS} provides the maximum braking force for the ABS system; V the current vehicle speed, V forward vehicle speed; $T_1$is the operating time of the braking system, T_2 is the braking force rise time, T_3 is the maximum holding time of the braking force, D is the initial distance between the leading car and the car, M is the mass of the vehicle, δ is the conversion coefficient of the rotating mass of the vehicle, C_D air resistance coefficient。

3.2 Model predictive control

Rewriting equation (5) as an incremental model, the form of the incremental model is as follows:

$$\begin{cases} \Delta x(k+1) = A_d \Delta x(k) + B_d \Delta u(k) + c_d \Delta v \\ y_{(k)} = G\Delta x + y(k-1) \end{cases} \tag{18}$$

At time k, with $\Delta x(k)$ as the starting point for predicting the future dynamics of the system, the state from time k to $k+p$ and the predicted output from $k+1$ to $k+p$ can be predicted from the previous formula. Then, the prediction output matrix of the prediction time domain system can be expressed as follows：

$$Y_p(k+11k) = S_x \Delta x(k) + Iy(k) + S_u \Delta u(k) + s_w \Delta w(k) \tag{19}$$

whereS_x，I，S_w，S_u is the coefficient matrix of the prediction equation. To meet various objectives such as safety, fuel economy, and comfort in the control process, the following objective function is used.

$$J(x(k), \Delta u(k), m, p) = (\|\varphi_y(y_p(k+1|k - R(k+1)\|^2 + \|\varphi_u \Delta u(k)\|^2) \tag{20}$$

where φ_y , φ_u are the weighted matrices of prediction output and control input, respectively, where $R(k+1)$ is the reference input:

Therefore, the cost function to satisfy various optimization objectives can be expressed as follows:

$$\min_{\Delta_u(k)}\ J\left(Y_p(k),\ \Delta u(k), m, p\right) \tag{21}$$

In order to achieve the optimal control effect under multi-objective conditions, the weight matrix $\varphi_y(k), \varphi_u(k)$ in the objective function should be selected reasonably. where, $\varphi_y(k)$ and $\varphi_u(k)$ have the following forms:

$$\varphi_y = \begin{bmatrix} w_d(k) & 0 & 0 \\ 0 & w_v(k) & 0 \\ 0 & 0 & w_a(k) \end{bmatrix} \tag{22}$$

$$\varphi_u(k) = w_a(k) \tag{23}$$

where, the weight $w_d(k)$ is the distance error between vehicles, the weight $w_v(k)$ is the speed error, the weight $w_a(k)$ is the acceleration of the vehicle, and the weight w_u(k) is the output of control.

4 NUMERICAL SIMULATION

The prediction horizon N_P = 20 and the control horizon N_c= 5 and $N = 5$ are chosen to be as small

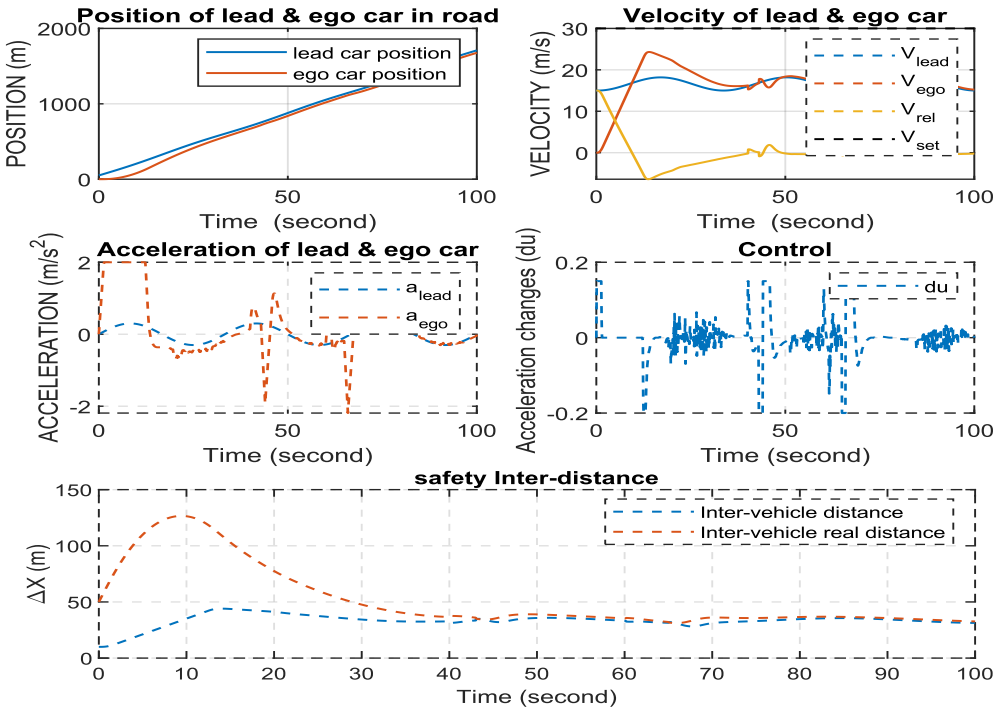


Figure 2: multi-objective control variables

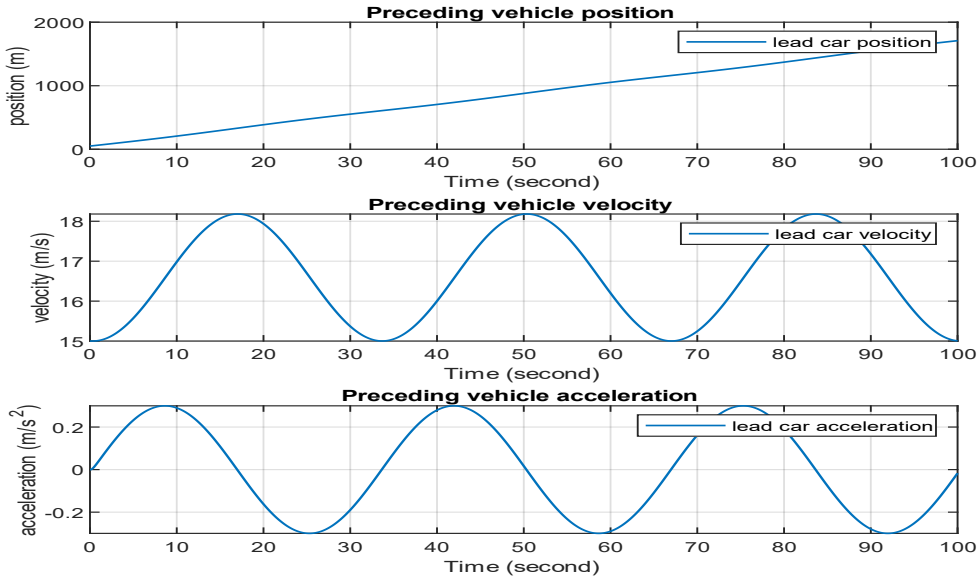


Figure 3: lead car work result

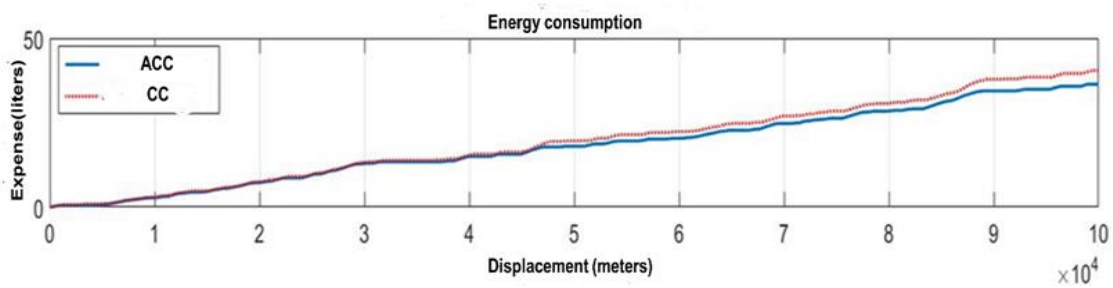


Figure 4: energy consumption comparison

as possible, the initial acceleration of the host $\dot{v}_0$is set to $14m / s^2$.

At the initial moment, the vehicle is following the target vehicle at a speed of 14 m/s. When t = 10 s, the preceding car changes lanes and drives away. At this moment, there is a vehicle with a speed of 20 m/s in 40 m ahead. The vehicle speeds up to reduce the distance error and then slows down to reduce the relative speed error as the distance between vehicles decreases. The simulation was performed on a laptop with an i9 processor and 32 GB RAM configuration.

Figure 2 shows that the multi-objective ACC system analyzed in our work with the MPC controller has achieved an almost precise longitudinal model between two vehicles, in the responses of the system it is shown that it is fulfilled in good terms with the prevention of possible collisions, maintaining a fairly safe inter-vehicular distance between the ego car and the lead car as main objectives and comfort as a minor objective simultaneously. Figure (a) is the speed variable between the ego car and the lead car, (b) the position of both vehicles, (c) is the acceleration of both vehicles, the ego car and the lead car, and figure (d) is the control effort made and (e) shows the inter-vehicle distance, while in Figure 4 we can see the energy consumption, the energy consumption of the proposed adaptive cruise control is compared to the energy consumption of a CC system, and it can be seen that the ACC consumes less fuel (energy). Figure 3 shows the results of the Lead car work with multiple objectives.

5 CONCLUSION

By analyzing an ACC system that satisfies multiple driving objectives, we use a model predictive control algorithm that can greatly and effectively, and optimally improve its constraints and multi-objective optimization problems compared to controllers such as PID or LQR.

(1) Using multi-objective analysis, a time-varying model predictive controller that can effectively deal with constraints and multi-objective optimization problems is used as the superior controller of the system.

(2) In order to cope with complex driving conditions, a real-time update strategy of weights under different working conditions is proposed, so that the vehicle has different target functions under different working conditions to improve the performance of the vehicle. ACC system.

The numerical simulations made from the data of a real vehicle conclude that the controller with weight adjustment in real-time reduces large energy consumption, the comfort conditions are optimal, and the inter-vehicle distance is quite stable.

REFERENCE

[1] Takahama, T. and D. Akasaka, *Model predictive control approach to design practical adaptive cruise control for traffic jam.* International journal of automotive engineering, 2018. **9**(3): p. 99-104.

[2] Al-Gabalawy, M., N.S. Hosny, and A.-h.S. Aborisha, *Model predictive control for a basic adaptive cruise control.* International Journal of Dynamics and Control, 2021. **9**(3): p. 1132-1143.

[3] Wei, Z., et al., *End-to-end vision-based adaptive cruise control (ACC) using deep reinforcement learning.* arXiv preprint arXiv:2001.09181, 2020.

[4] Nie, Z. and H. Farzaneh, *Adaptive cruise control for eco-driving based on model predictive control algorithm.* Applied Sciences, 2020. **10**(15): p. 5271.

[5] Shakouri, P., A. Ordys, and M.R. Askari, *Adaptive cruise control with stop&go function using the state-dependent nonlinear model predictive control approach.* ISA transactions, 2012. **51**(5): p. 622-631.

[6] Lin, Y.-C., H.-C. Hsu, and I.-C. Kuo. *An eco-cruising control systems using nonlinear predictive control approach*. in *2016 International Automatic Control Conference (CACS)*. 2016. IEEE.

[7] Vajedi, M. and N.L. Azad, *Ecological adaptive cruise controller for plug-in hybrid electric vehicles using nonlinear model predictive control.* IEEE Transactions on Intelligent Transportation Systems, 2015. **17**(1): p. 113-122.