

# Study on the Electric Vehicle Adaptive Cruise Control Based on the Model Predictive Control Algorithm



Zhenhai Gao and Hai Song

**Abstract** In this chapter, according to the characteristics of the electric vehicle regenerative braking, considering safety, economy, and comfort in adaptive cruise control, a kind of electric vehicle adaptive cruise control algorithm has been built, which has two layers, the decision layer calculates the optimal acceleration based on the model predictive control algorithm and vehicle longitudinal control layer tracks the optimal acceleration with fuzzy algorithm. Then, using the software Amesim and Simulink to simulate the typical working condition simulations, the results show that the control algorithm can effectively realize electric vehicle adaptive cruise, and capture braking energy.

**Keywords** Electric cars · Adaptive cruise control · Model predictive control

## 1 Introduction

The adaptive cruise system is a kind of advanced driving assistant systems, through the sensor such as millimeter wave radar obtaining the velocity and distance from ahead vehicle, and by controlling the host vehicle speed it can keep the safe distance from the other vehicles to implement adaptive cruise [1, 2]. The adaptive cruise technology was developing rapidly, many scholars did deep research in it, Gennaro Nicola Bifulco et al. analysed the driving characteristics using the learning feature of human to achieve adaptive cruise [3], Seungwuk Moon et al. used the collision time index and data of drivers without collision based on the confusion matrix method to design the whole speed range of adaptive cruise, and tested in real vehicles [4].

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With the increasing number of car in recent years, automobile exhaust pollution was more and more serious. The electric vehicles with low emissions, environmental protection began to get more and more application. In the field of new energy, vehicle's advanced driver assistance technologies, Behnam Ganji, Abbas z. Kouzani et al. used sliding mode control with hybrid vehicle as research object to achieve the technology of adaptive cruise [5], Sebastien Glaser et al. proposed the green intelligent adaptive cruise system, using the pure electric vehicle as the research platform, introduced how to use the electric car energy recovery characteristics to design the adaptive cruise system.

From above, it can be seen that there are the similarities and differences between the electric vehicle adaptive cruise system and the traditional vehicle adaptive cruise system. For the comprehensive solution of the electric vehicle safety, energy saving and comfort in the adaptive cruise, with the characteristics of regenerative braking of electric vehicle, we proposed an electric vehicle adaptive cruise control system to realize adaptive cruise considering electric motor properties, the giving control system consists of the decision layer and the vehicle longitudinal control layer. The decision layer computes the optimal vehicle acceleration by the information from outside sensors. Through calculating the vehicle longitudinal control layer to calculate the motor and the braking system control quantity, then it implements tracking the vehicle acceleration accurately and maximizes the recovery of braking energy.

## 2 The Decision Algorithm Design

Model predictive control is a method of optimization control, which solves the sampling process of a limited open-loop optimal problem in each control action to obtain the optimal control effect [7]. In control process, the initial state of the optimal control problem is the current state, and the solution of optimal control sequence only implemented on the first control action.

### 2.1 Prediction Model

We use the pure electric vehicle as the research object for analysis. The movement of vehicles relations and the host vehicle dynamic states are used as a predictive model. As shown in Fig. 1, according to Newton's motion laws, we get the electric vehicle longitudinal dynamics Formula (1); in Formula (1),  $D$  is the distance between the host vehicle and ahead vehicle;  $v_{rel}$  is relative speed of two vehicles;  $T_s$  is the time step;  $a_h$  is the acceleration of the host vehicle;  $v_h$  is the host vehicle velocity;  $j$  is the jerk of the host vehicle;  $u(k)$  is the incremental acceleration of the input system. In the real scenario,  $D$  and  $v_{rel}$  are measuring by sensors such as millimeter wave radar, and other information measuring by electric car sensors, reading on the can bus.



Fig. 1 The prediction model

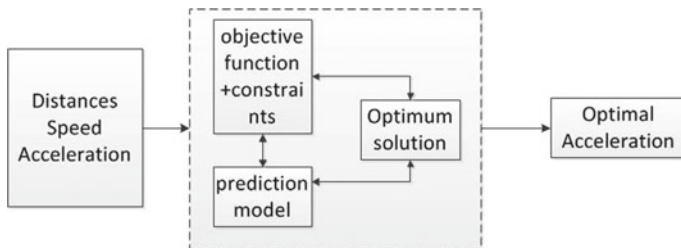


Fig. 2 The decision controller frame

$$\begin{cases} D(k+1) = D(k) + v_{rel}(k)T_s - \frac{1}{2}a_h(k)T_s^2 \\ v_{rel}(k+1) = v_{rel}(k) - a_h(k)T_s \\ v_h(k+1) = v_h(k) + a_h(k)T_s \\ a_h(k+1) = (1 - \frac{T_s}{\tau})a_h(k) + \frac{T_s}{\tau}u(k) \\ j(k+1) = -\frac{1}{\tau}a_h(k) - \frac{1}{\tau}u(k) \end{cases} \quad (1)$$

## 2.2 Model Predictive Controller Design

According to the mathematical vehicle model, which was established in Formula (1), we can establish a framework for decision controller shown in Fig. 2.

According to the given vehicle, following movement Formula (1), it can define the model state:  $x(k)$ , which is  $x(k) = [D(k), v_{rel}(k), v_h(k), a_h(k), j(k)]$ . Then, it can be written as matrix form

$$x(k+1) = Ax(k) + Bu(k) \quad (2)$$

In which

$$A = \begin{bmatrix} 1 & 0 & T_s & -\frac{1}{2}T_s^2 & 0 \\ 0 & 1 & 0 & -\frac{1}{2}T_s^2 & 0 \\ 0 & 0 & 0 & -T_s & 0 \\ 0 & 0 & 0 & 1 - \frac{T_s}{\tau} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau} & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{T_s}{\tau} \\ \frac{1}{\tau} \end{bmatrix}$$

### 2.2.1 The Objective Function

The objective function is the cost function to achieve electric vehicle optimal performance on the road. The performance of the electric vehicle mainly evaluating the safety, energy consumption, and convenience [8]. Generally, using distance to evaluate safety, with the variable time headway model [9], the optimization goal is to minimize the real and desired distance between the host vehicle and ahead vehicle.

Electric vehicles use motor to drive, its energy consumption evaluation characterization through battery charged state, also can be described by motor power change. So it can be used for the change of the output torque of the motor to measure the energy consumption. The electric vehicle acceleration is proportional to the motor torque so that we can use the electric vehicle acceleration to describe the status of energy consumption, the optimization goal of energy consumption is to minimize the electric vehicle acceleration.

In vehicle dynamics, the vehicle acceleration and jerk commonly are described as the vehicles driving smooth while adding speed or subtracting speed. The cost function  $J$  can be used to evaluate the electric vehicles comfort. The vehicle comfortable optimization goal is to minimize the jerk and acceleration.

According to the above optimization goal, the cost function  $J$  of model predictive controller is designed. The cost function  $J$  is used to predict the optimal control in each control iteration step. The controller predictive time domain is  $N_p$ , control item domain is  $N_c$ . From above the cost function,  $J$  needs safety, comfortable, and energy consumption goal to minimize, Formula (2) shows the matrix form of the vehicle state. We put the cost function in the prediction of deviation value domain and control domain as shown in (3), in which the first part calculates the predicted field deviation value, the second part calculates the control domain system accumulated value of input amount. On each control cycle through solving the minimizing the cost function  $J$ , it can be calculated the optimal acceleration value of the decision layer.

$$J = \sum_{i=1}^{N_p} \|x(k+i|t) - x_{\text{ref}}(k+i|t)\|_Q^2 + \sum_{i=1}^{N_c} \|u(k+i|t)\|_R^2 \quad (3)$$

### 2.2.2 The Constraint

Vehicle adaptive cruise system is usually working in a safe range, the system runs in a fixed range generally, the control quantity and control increment quantity need to limit, so system required the constraints

$$u_{\min} = -5.5 \text{ m/s}^2, \quad u_{\max} = 2.5 \text{ m/s}^2, \quad \Delta u_{\min} = -2 \text{ m/s}^3, \quad \Delta u_{\max} = 2 \text{ m/s}^3$$

The controller need to control every step of constraints that

$$u_{\min}(t+k) \leq u(t+k) \leq u_{\max}(t+k) \quad k = 0, 1, \dots, N_c - 1$$

$$\Delta u_{\min}(t+k) \leq \Delta u(t+k) \leq \Delta u_{\max}(t+k) \quad k = 0, 1, \dots, N_c - 1$$

## 3 The Vehicle Longitudinal Control Algorithm Design

From above, the optimal acceleration is calculated by decision layer, we need to change the optimal acceleration to the input of motor and braking system, it needs to calculate the control quantity. So the vehicle longitudinal control layer is established as a control block diagram shown in Fig. 3, which uses the optimal acceleration to control quantity for the motor and braking system.

The electric vehicle can recover energy while the vehicle is braking, so we establish a fuzzy decision module in the controller to calculate the regenerative braking and traditional braking rate. The input of decision module is the vehicle speed and acceleration, the output is the motor regenerative braking percentage in total braking so that the controller is able to use the acceleration error to calculate the control quantity the motor and the braking system of electric vehicle.

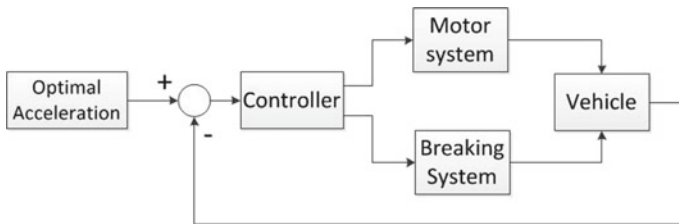


Fig. 3 The framework of control layer

## 4 Simulation

### 4.1 Model Building

In the field of multidisciplinary complex system modeling and simulating platform software Amesim, a kind of electric vehicle physical model has been structured, shown in Fig. 4.

Reference controller algorithm which given in the second quarter, with the visualization simulation tool simulink, the upper model predictive controller model is built, as shown in Fig. 5. The top decision-making unit, which uses model predictive control algorithm in the second quarter, is encapsulated to the S function module of simulink to achieve calculating the optimum acceleration. Lower level executive level controller uses fuzzy algorithm, through rules designed to calculate the braking force distribution coefficient, and then the input optimal acceleration of the control layer is changed into actual control quantity of motor and the braking system, then the control quantity is sending to the Amesim electric vehicle model. By the method of Amesim, turning its model into S function of simulink, then implementation to simulink as the main body of the joint simulation.

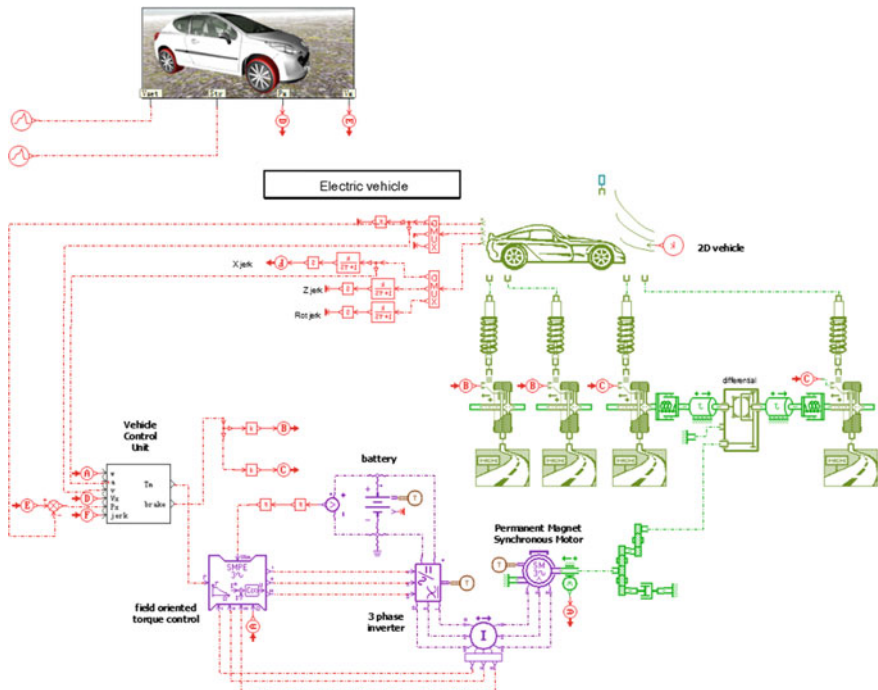


Fig. 4 The host vehicles and ahead vehicle model

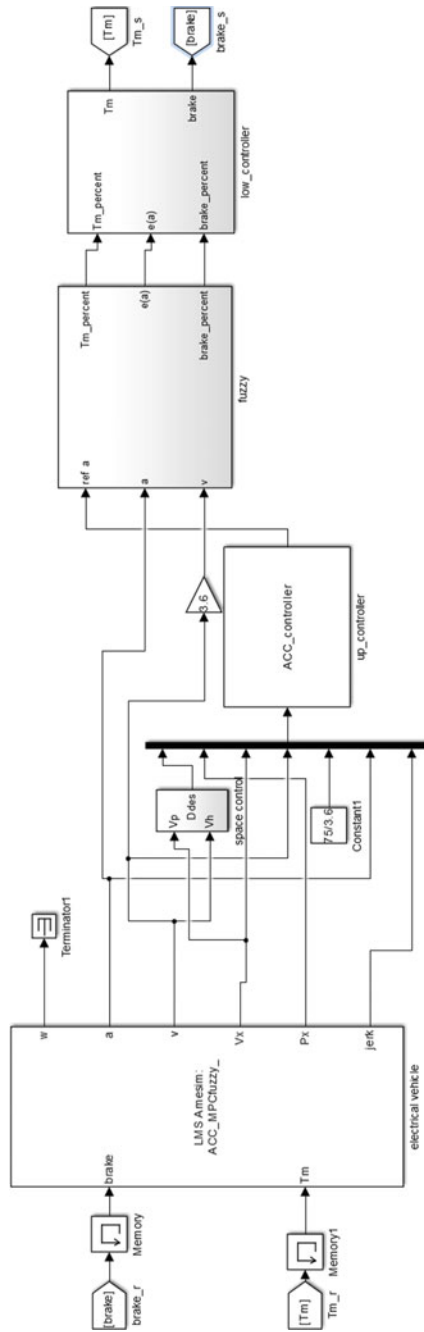


Fig. 5 The electric vehicle controller model in simulink in Amesim

## 4.2 The Simulation Results

We select three typical working conditions of adaptive cruise for electric vehicle adaptive cruise simulation experiments, respectively is linear variable speed cruise condition, following condition, cut in following condition.

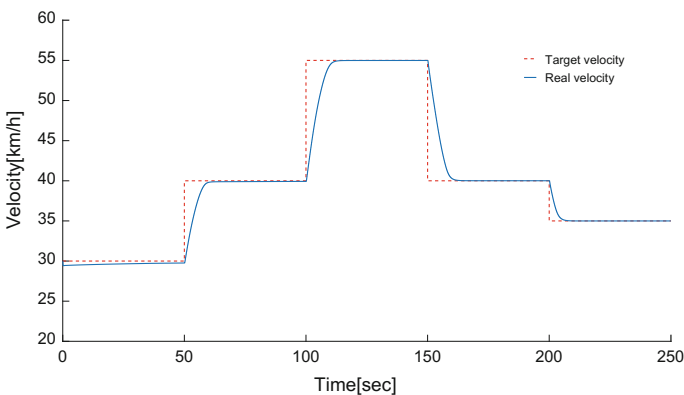
### 4.2.1 Linear Variable Set Speed Cruise Condition

As shown in Fig. 6, dotted line in the figure represents the target speed, and the solid line shows the actual speed. First, the vehicle speed stability to 30 km/h, at  $T = 50$  s when the target speed is set to 40 km/h, at  $T = 100$  s when the target speed is set to 55 km/h, at  $T = 150$  s when the target speed is set to 40 km/h, at  $T = 200$  s when the target speed is set to 35 km/h. As you can see by the picture, the target speed change, speed on the local immediately follow the target speed, smooth change can be stable after 10 s to the target speed.

The cruise condition decision-making target acceleration and the actual vehicle acceleration as shown in Fig. 7, can be seen from the figure in the actual vehicle acceleration and speed of a target price it is better to follow, to ensure the adaptive cruise control system, the realization of the function of cruise control.

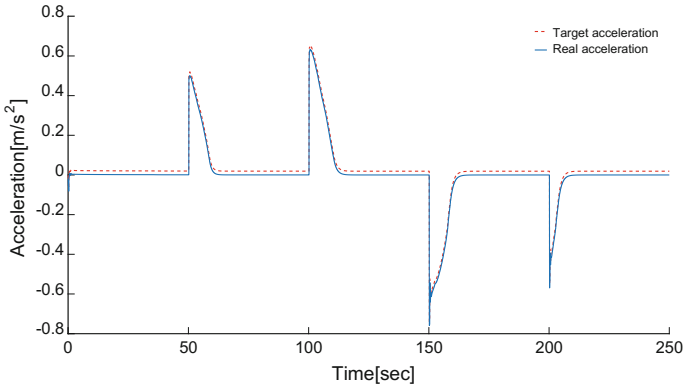
### 4.2.2 The Following Condition

As shown in Fig. 8, the host vehicle is driving with speed of 55 km/h, the ahead vehicle in the same lane driving at 40 km/h, at start two vehicles are far away (100 m); with the gap between two vehicles shrinking, the host vehicle switches to the following pattern, keeps the distance in 20 m, and makes the speed as same as the ahead vehicle.

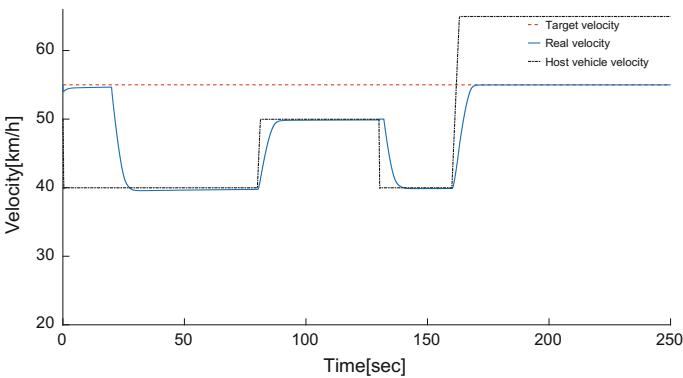


**Fig. 6** The velocity of cruise condition time history curve





**Fig. 7** The acceleration of cruise condition time history curve



**Fig. 8** The velocity of following condition time history curve

Finally, the ahead vehicle accelerates to 65 km/h, with the distance increasing, when the distance large than a certain value, adaptive cruise control system keeps the set speed of 55 km/h. It can be seen from Fig. 8, when the host vehicle closes to the ahead vehicle, the speed of the host vehicle reducing gradually, then it reaches to the same speed as the ahead vehicle. In the process of following, no matter the ahead vehicle accelerating or decelerating, the host vehicle can follow the velocity of the ahead vehicle quickly and smoothly. When the ahead vehicle is driving away, the host vehicle can restore the cruise control, and keep the speed to the set value.

The acceleration of decision by cruise condition and the actual vehicle acceleration are shown in Fig. 9, it can be seen from the figure that the vehicle’s actual acceleration and speed of target following target acceleration and speed well, shown that the host vehicle’s actual acceleration can follow the target acceleration quickly and accurately. In this condition, the distances between the two vehicles are shown in Fig. 10, you can see when closing to the ahead vehicle, the adaptive cruise system can control the distance of the ahead vehicle and host vehicle effectively, then keep a safe distance.

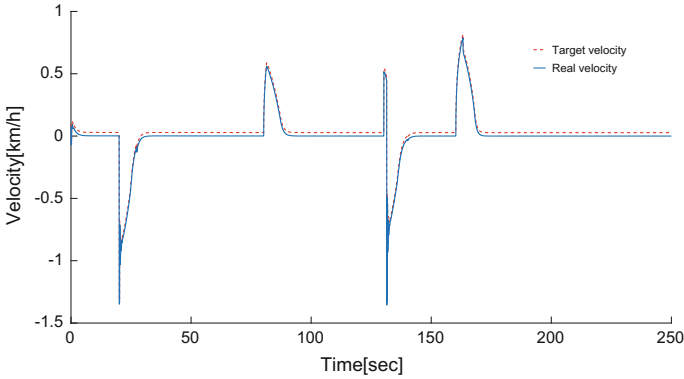


Fig. 9 The acceleration of following condition time history curve

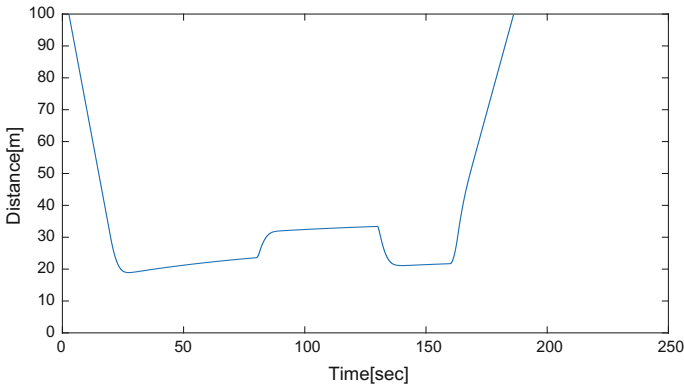


Fig. 10 The distance of following condition time history curve

### 4.2.3 The Cut in Following Conditions

As shown in Fig. 11, the host vehicle is driving with speed of 75 km/h. The ahead vehicle with speed of 80 km/h cut in 30 m place away in the front lane, and to slow down to 55 km/h, again after uniform speed to 40 km/h, and then accelerate to 70 km/h and switch lanes. Can be seen from Fig. 12 vehicle ahead after cut into the lane on the local deceleration, began to slow to follow on the local vehicle ahead, in the process of vehicle ahead change the speed still can follow the change of the velocity.

It can be seen from the Fig. 13, adaptive cruise system effectively control the distance between the host vehicle and ahead vehicle, in the case of sharp slowdown of ahead vehicle the system can ensure the safe distance.

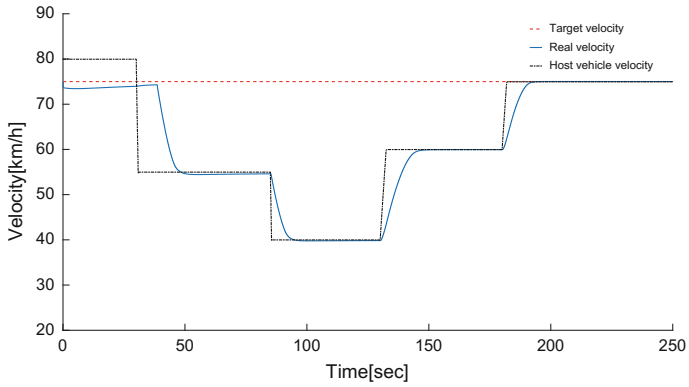


Fig. 11 The velocity of cut in condition time history curve

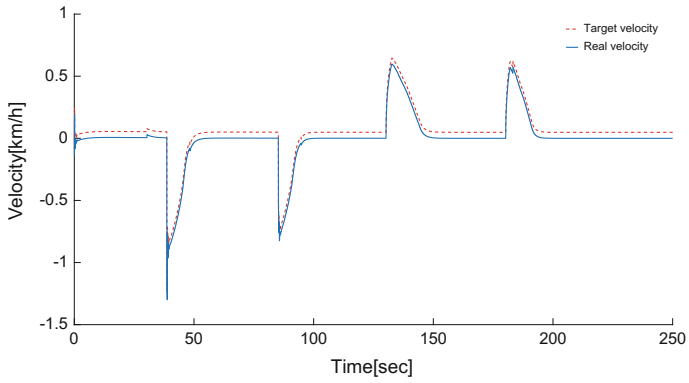


Fig. 12 The acceleration of cut in condition time history curve

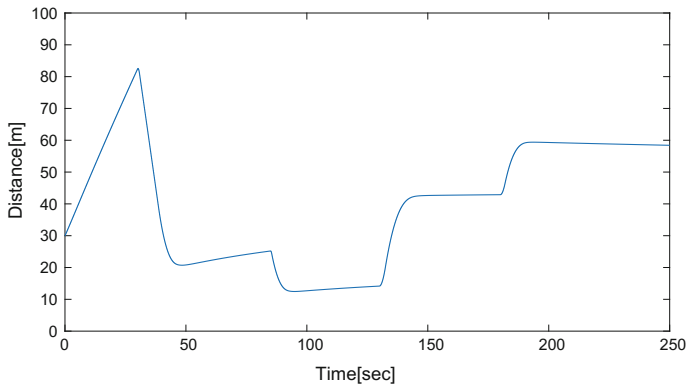
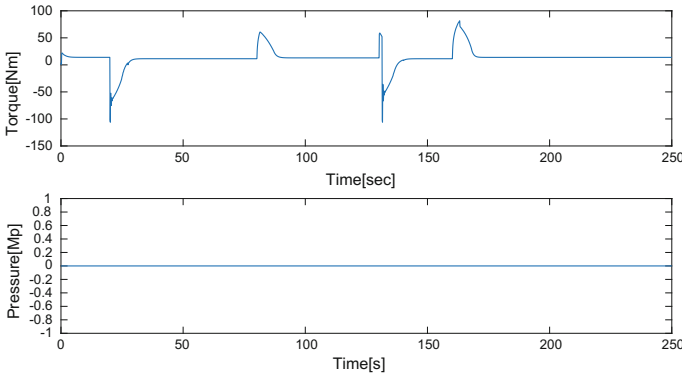


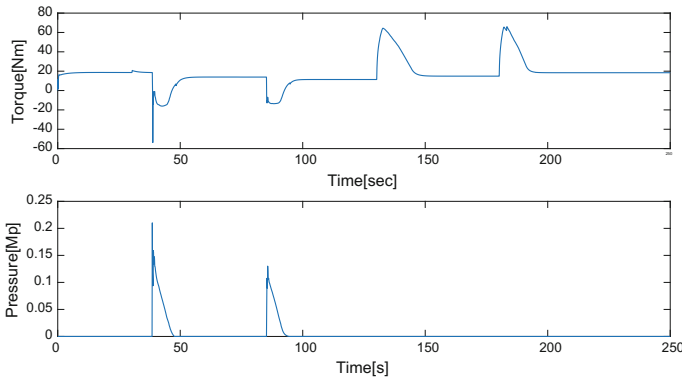
Fig. 13 The distance of following condition time history curve

### 5 Analysis

From above, the electric vehicle adaptive cruise control system did well work in the three typical working conditions. The torque of electric vehicle motor drive system and the master cylinder pressure of the braking system are plotted as shown in Fig. 14, in the following conditions, the electric vehicle can achieve adaptive cruise control just by regenerative braking, shows that the lower fuzzy decision is able to calculate the distribution ratio of regenerative braking correctly, achieve the goal of reducing energy consumption. It can be seen in Fig. 15, due to the sharp slowdown of the ahead vehicle speed, motor, and brake system provide braking at the same time to achieve the demand of deceleration. The simulation results show that the proposed



**Fig. 14** Motor torque and brake system master cylinder pressure value of following condition time history curve



**Fig. 15** Motor torque and brake system master cylinder pressure value of cut in condition time history curve

algorithm in the cut in and cut out working conditions of can effectively implement the following control, and can realize the cruise and according to the actual situation of switching.

## 6 Conclusion

In this chapter, considering adaptive cruise system the safety, energy consumption, comfort requirements, with the characteristics of the regenerative braking of electric vehicle, we proposed decision algorithm based on model predictive control algorithm and the vehicle longitudinal control algorithm, then the simulation experiments are taken. The conclusion is as follows:

- (1) Thought three typical working conditions of adaptive cruise simulation, verify the algorithm designed realize the adaptive cruise control.
- (2) Under different working conditions, the algorithm can adjust output to realize braking energy as design.

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