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STUDY ON ADAPTIVE CRUISE CONTROL STRATEGY FOR PURE ELECTRIC VEHICLE CONSIDERING BRAKING ENERGY RECOVERY

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ABSTRACT

This paper studies the control strategy for adaptive cruise control (ACC) system on pure electric vehicle (PEV) in the car-following process. The hierarchical control structure is adopted for the ACC system, and the structure contains upper controller and lower controller. In the upper controller, multiple objectives including the safety, tracking, comfort and energy consumption are optimized in a model predictive control (MPC) framework. In the lower controller, the energy is recovered during braking. So the energy economy is improved by reducing energy consumption and increasing energy recovery. The proposed ACC control strategy is evaluated in simulation. The simulation results show that safety and tracking are guaranteed, and the comfort and energy economy are improved significantly.

Keywords: pure electric vehicle, adaptive cruise control, multiple objectives, model predictive control, braking energy recovery

1. INTRODUCTION

Recently, PEV and autonomous driving have made great progress [1, 2]. Combining these two advance vehicle technologies, vehicles can obtain good performances in terms of safety, dynamic, comfort, economy. When a vehicle (front vehicle) occurs in front of the PEV with ACC function (ego vehicle), the driving process is called the car-following process. During the car-following process, the host vehicle should keep a safe spacing by control the driving system and braking system to avoid collision. Recovering energy during braking can effectively improve energy economy.

For the design of ACC controller, various control algorithms that is the fuzzy control, sliding mode control, PID and machine learning have been applied. MPC is one of the widely used algorithms in the research of ACC, because it can implement multi-objective receding horizon optimization under various constraints. In [2], a nonlinear MPC technology was applied to ecological ACC for plug-in hybrid electric vehicle to improve the safety and fuel economy. In [3], a predictive cruise control was proposed, and the ACC system is used to support the driver to track the energy optimal velocity trajectory.

For the regenerative braking, some researches have been finished. In [4], a sliding mode controller was designed to balance the antilock braking force and regeneration braking force. In [5], the genetic algorithm was applied to increase the braking energy recovery based on ensuring the vehicle stability. In [6], the braking force is distributed according to the ideal distribution curve.

However, there is rare researches on combining ACC and braking energy recovery. This paper focus on it. The contributions of this paper are as follows: firstly, the energy economy during the car-following process is improved by reducing the energy consumption and improving the braking energy recovery; secondly, the rate of change of acceleration (jerk) is introduced into the longitudinal dynamic model; thirdly, the optimized reference trajectories are applied to smooth the system response characteristics.

2. PEV MODEL

The front-wheel drive PEV is chosen as the modeling object. In the braking process, the motor drives the final drive to apply braking force to the front axle. Since the motor braking is affected by various factors, it is needed to make a coordination for the hydraulic braking to complete the braking process. The hydraulic braking is implemented through controlling the hydraulic pressure adjustment unit of the electronic stability control system (ESC).

The vehicle model is designed in CarSim software, but the complete powertrain model of PEV isn't included in the Carsim, so an external simulink models of motor and battery need to be added. The lithium battery and permanent magnet synchronous motor are selected for PEV in this paper. Internal resistance model is used to build the battery model. There are many factors affecting the braking force of the motor. This paper mainly considers the torque-speed characteristic. The efficiency of the battery and motor during drive and brake is also considered in the PEV model. The key parameters of PEV model are presented in Table 1. Where, M_v is the vehicle weight, A is the front area, C_w is the drag coefficient, f_r is the coefficient for rolling resistance, ρ_{air} is the air density, P_{M_max} is the maximum power of the motor, SOC_{ini} is the initial value for SOC, Q_{bat} is the total battery capacity.

Table 1: Key parameters of PEV model

Symbol	Values	Symbol	Values
M_v	1550kg	ρ_{air}	1.206kg/m^3
A	2.28m^2	P_{M_max}	87KW
C_w	0.36	SOC_{ini}	0.6
f_r	0.015	Q_{bat}	93Ah

3. LOWER LEVEL CONTROLLER

In the hierarchical structure, the upper controller is used to obtain the control command; the lower controller is used to determine the brake and drive to track the control command. The distribution strategy for braking force is an important component of lower controller in this paper.

The distribution strategy for braking force is the focus of the energy recovery system, including the braking force distribution for the front axle and rear axle, and the distribution for the motor braking force and hydraulic braking force. The energy recovery is carried out as much as possible based on meeting the safety for the braking process. The distribution of braking force for PEVs needs to meet the regulations of economic commission of Europe (ECE).

The brake strength z is an important variable during the braking process. When $z<z_1$, a lower limit of the braking force for front axle isn't required in the regulation, braking force is obtained only by motor braking on front axle. When $z_1<z<z_2$, braking forces on front axle and rear axle are distributed along the lower limit of ECE regulations. When $z_2<z<z_3$, the braking strength is high, the motor braking achieves its maximum, the braking force for front axle is constant, and the hydraulic braking force for the rear axle is increased. When $z>z_3$, the motor brake is abandoned, and the braking forces on front axle and rear axle are distributed along the line of braking force distribution to ensure safety and take advantage of the ground attachment characteristics. During the process of braking force distribution, if the motor braking force is insufficient, it is compensated through the hydraulic braking force.

4. UPPER LEVEL CONTROLLER

4.1 Longitudinal dynamic control model

The longitudinal dynamic control model of ACC system for PEV is modeled. The spacing, relative speed, and the speed, acceleration and jerk of the ego vehicle are taken as the state variables, and the acceleration for the front vehicle is regarded as the system disturbance. The following discrete state equation model is obtained:

$$x(k+1) = Ax(k) + Bu(k) + Gw(k) \tag{3}$$

$$x(k) = [\Delta s(k), v(k), v_e(k), a(k), j(k)] \tag{4}$$

$$w(k) = a_l(k) \tag{5}$$

where, $\Delta s(k)$ is the spacing, $v_e(k)$ is the relative velocity, $v(k)$, $a(k)$, $j(k)$ are the velocity, acceleration and jerk of host vehicle. And $u(k)$ is the control output of upper level. And $w(k)$ is the disturbance of ACC system.

The matrix in the Eq. (3) are as follows:

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

where, T_s is the sampling time of the ACC system and τ is the ACC system time constant due to limited bandwidth.

The performance vectors are defined as follows:

$$y(k) = [\delta(k), v_e(k), a(k), j(k)] \tag{6}$$

where, δ is the error of actual spacing and the expected spacing, the expected spacing adopts a constant headway strategy. The δ is defined as follows:

$$\begin{aligned} \delta(k) &= \Delta s(k) - \Delta s_{des}(k) \\ &= \Delta s(k) - (d_0 - t_h \cdot v(k)) \end{aligned} \tag{7}$$

where, $\Delta s_{des}(k)$ is expected spacing, d_0 is a fixed safe spacing as the vehicle speed reaches zero or low, and t_h is the expected time headway.

4.2 Multi-objective optimization algorithm

The multi-objective optimization algorithm is designed with the consideration of the safety, tracking, comfort and energy consumption.

To ensure the tracking, it requires that the spacing approaches the expected spacing, the velocity of the ego vehicle approaches the velocity of the front vehicle.

$$\text{Objectives: } \delta(k) \to 0, v_e(k) \to 0, \text{as } k \to \infty \quad (8)$$

To improve the comfort, the absolute value of acceleration and jerk for ego vehicle should be minimized:

$$\text{Objectives:} \begin{cases} \min |a(k)| \\ \min |j(k)| \end{cases} \quad (9)$$

To reduce the energy consumption, the absolute value of control command for ego vehicle should be minimized:

$$\text{Objective: } \min |u(k)| \quad (10)$$

To ensure that the ego vehicle can follow the target vehicle smoothly, the exponential decay function is introduced as the reference trajectory of the performance vector to be optimized. The response curves of system are smoothed as follows:

$$y_r(k+i) = \begin{bmatrix} \rho_\delta{}^i & & & \\ & \rho_v{}^i & & \\ & & \rho_a{}^i & \\ & & & \rho_j{}^i \end{bmatrix} y(k) \quad (11)$$

where, ρ_δ, ρ_v, ρ_a and ρ_j are the reference trajectory coefficient corresponding to the δ, v_e, a and j, and values of these coefficients are between 0 and 1. Along the reference trajectory y_r, the variables in the performance vector y will approach 0 smoothly.

To ensure that there is no collision between the two vehicles, the spacing should be greater than the minimum safe vehicle spacing.

$$\text{Constraints: } \Delta s(k) \geq d_c \quad (12)$$

Moreover, considering the limitation of the capacity of the host vehicle, it is necessary to limit the speed, acceleration, jerk and control variable of the host vehicle. The constraints are as follows:

$$\text{Constraints:} \begin{cases} v_{\min} \leq v(k) \leq v_{\max} \\ a_{\min} \leq a(k) \leq a_{\max} \\ j_{\min} \leq j(k) \leq j_{\max} \\ u_{\min} \leq u(k) \leq u_{\max} \end{cases} \quad (13)$$

From above analysis, it can get an objective function in an MPC framework as follows:

$$J = \sum_{i=1}^{p} [\hat{y}_p(k+i/k) - y_r(k+i)]^T Q [\hat{y}_p(k+i/k) - y_r(k+i)] + \sum_{i=0}^{m-1} u(k+i) R u(k+i) \quad (14)$$

In Eq. (14), $\hat{y}_p(k+i/k)$ is the prediction of the performance vector for $k+i$ moment at k moment, p and m are predictive horizon and control horizon, respectively. Q and R are the weight coefficient in the objective function. The Eq. (14) combined with the constraints (12) and (13) can be transformed into an online constrained quadratic programming problem. And it can be solved directly by using Matlab optimization toolbox.

5. METHODS

To evaluate the performances of the proposed ACC control strategy, two different strategies are compared, which are the proposed strategy that considers comfort, energy economy, safety and tracking (OBJ_CEST) and the strategy that only considers safety and tracking (OBJ_ST), in OBJ_ST, the optimized reference trajectories aren't applied to the objective function, and the regenerative braking isn't considered in lower controller or PEV model.

Whether the spacing is bigger than the minimum safe spacing is regarded as the evaluation for the safety. The tracking is measured by the performance of regulating the spacing and the velocity of ego vehicle to the expected spacing and velocity of front vehicle, respectively. Comfort is evaluated by the maximum value of jerk's absolute value. Energy economy is estimated by the change of SOC. The strategies are designed and verified in the Matlab/Simulink.

Scenario in simulation is set as follows: Following a front vehicle with varying speed. The initial spacing is 50 m, the initial speed of front vehicle and ego vehicle are 15m/s and 10m/s, respectively. And the acceleration amplitude of front vehicle is 2 m/s^2. The main parameters for the multi-objective optimization algorithm are listed in Table 2.

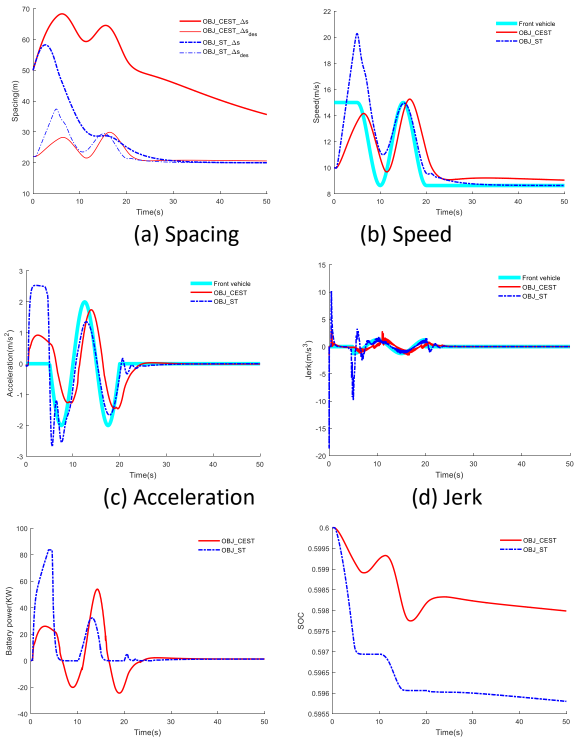
Table 2: Main parameters for the optimization algorithm

Symbol	Values	Symbol	Values
Ts	0.2s	u_{min}	-5.5m/s^2
t_h	1.5s	u_{max}	2.5m/s^2
τ	0.15s	j_{min}	-3m/s^3
d_0	7m	j_{max}	3 m/s^3
d_c	5m	ρ	0.94
v_{min}	0 m/s	Q	diag{1,10,1,1}
v_{max}	36m/s	R	1

a_{min}	-5.5m/s^2	T	50s
a_{max}	2.5m/s^2	-	-

6. RESULTS AND DISCUSSION

From Fig. 1 (a) and (b), it can be seen that the vehicle spacing is greater than minimum safety spacing in two control strategies, and the ego vehicle can track the desired vehicle spacing and velocity of front vehicle in two algorithms. Therefore, the safety and tracking can be ensured in both two control strategies.



(a) Spacing (b) Speed

(c) Acceleration (d) Jerk

(e) Battery power (f) SOC

Fig 1 Simulation results

From Fig. 1 (c) and (d), the maximum value of jerk's absolute value in OBJ_ST is 18.66m/s^3, which is out of the limits of perception (3m/s^3) that passengers can accept. However, the maximum value of jerk's absolute value in OBJ_CEST is always within the 3m/s^3. The comfort in OBJ_CEST is improved compared with the OBJ_ST. The reasons for this is that the jerk is strictly constrained, and the optimized reference trajectory is applied to smooth the response characteristics of the system. From Fig. 2 (e), it is shown that the battery power in OBJ_CEST changes between positive and negative. However, the battery power in OBJ_ST changes between zero and positive. From Fig. 2 (f), the change of SOC for two strategies are 0.0020 and 0.0042, respectively. The improvement of the energy economy for the OBJ_CEST is 52.03% compared with the OBJ_ST. The reasons for this is that the energy consumption is optimized in the upper controller and the braking energy recovery is considered in the lower controller in OBJ_CEST.

7. CONCLUSIONS

In this paper, a hierarchical control architecture is adopted. The proposed ACC control strategy is evaluated. Under the premise of meeting the safety and tracking, the proposed strategy has better performance in terms of the comfort and energy economy. The proposed ACC control strategy can improve the comfort for passengers and improve the energy economy for the car owner, so it can promote the wide application of ACC in PEV by. In the existing researches, MPC-based ACC control strategy is mostly verified by simulation. In the future, the proposed control strategy for ACC system based on MPC will be verified by real experiments.

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