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Energy-efficient longitudinal driving strategy for intelligent vehicles on urban roads

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Energy and environmental problems brought by automobiles are becoming more and more prominent. One promising way to solve these problems is to improve the energy efficiency of vehicles. The energy efficiency of a vehicle is not only related to vehicle performance, but also related to driving behavior. Combining longitudinal driving with intelligent transportation information can significantly improve energy efficiency [1]. Thus, energy-efficient longitudinal driving strategy based on intelligent transportation information is a research hotspot for manufactures and academics.

Many driving strategies have been proposed to improve energy efficiency by using upcoming traffic and road information [2]. Research indicates that longitudinal driving strategies can improve energy economy by approximately 20% from a theoretical perspective [3, 4]. Although the energy saving potential is considerable, related studies on model predictive control (MPC)-based strategies remain in theoretical analysis [5]. Supports from experimental results are lacking. The real-vehicle implementation of MPC-based strategies is a challenging task that involves three key issues. (a) How can upcoming road and traffic information be obtained and incorporated into the optimization system? (b) How can an MPC problem be formulated considering safety, comfort, and economy? (c) How can the MPC optimization problem be solved, such that the optimization can be implemented on real-time vehicle control unit?

In implementing the full-speed longitudinal control, one key issue relates to the stop-and-go scenarios [6]. Vehicles on urban roads are often at low speed conditions and with frequent stops and accelerations. Under these scenarios, the engine torque commands are difficult to track accurately due to large fluctuations. Meanwhile longitudinal dynamics contains an external disturbance of road slope. MPC-based strategies are inapplicable for stop-and-go scenarios due to the limited energy-saving potential. Therefore, fully autonomous driving requires a separate stop-and-go controller.

To address the aforementioned issues, an energy-efficient longitudinal driving strategy with stop-and-go function is proposed to achieve full-speed range driving. This strategy is based on high-definition (HD) map and comprises MPC-based and stop-and-go controllers. The MPC-based controller is discussed in [7]. The present study aims to discuss stop-and-go controller and provide important technical details that are not covered in [7]. The main contributions of this study are summarized as follows. First, the stop-and-go controller is designed for low speed conditions. Second, the road intersection information of HD map is incorporated into the proposed driving strategy. Third, an efficient lookup table algorithm is proposed to reduce the computa-

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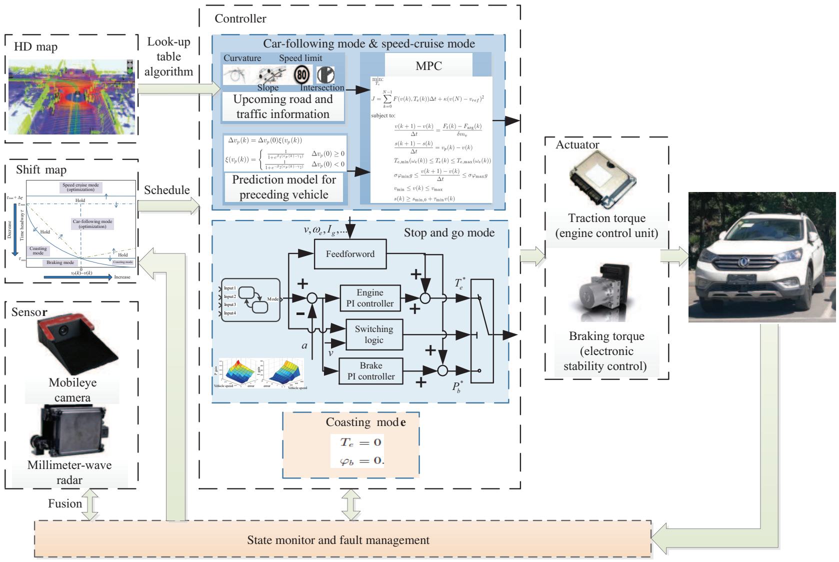

Figure 1 (Color online) Control architecture of the proposed longitudinal driving strategy.

tional burden of predictive horizon. Fourth, new experimental results, including comparison results with and without the road slope signal, comparison results with different driving styles of different drivers, and road test results in Wuhan of China, are presented.

Control scheme. The control architecture of the proposed longitudinal driving strategy is shown in Figure 1. The structure comprises sensor, HD map, shift map, actuator, controller and state monitor and fault management modules. The sensor module identifies and filters surrounding car-following targets through data fusion from Mobileye camera and millimeter-wave radar and then provides inter-vehicle states for the controller. The shift map is introduced to schedule the different operating modes for the controller. The controller is divided into four modes, namely, car-following, speed-cruise, coasting and stop-and-go modes. The control laws of car-following and speed-cruise modes are derived from the optimization problem, where the upcoming road and traffic information is provided by the HD map module. The desired control commands are executed by the engine control unit and electronic stability control system. The state monitor and fault management module is responsible for the functional safety of the entire system.

Stop-and-go controller. To obtain a satisfactory control performance, a hierarchical control scheme is proposed for low speed conditions. The control system is split into two subsystems with different dynamic properties. The car-following subsystem (high level) is linear, whereas the acceleration-tracking subsystem (low level) is nonlinear with an unmeasurable road slope. A proportional integral (PI)-based inter-distance control scheme and a feedforward-feedback approach are adopted for the high and low levels, respectively. The interaction between these two levels is guaranteed by the longitudinal acceleration of the vehicle, which is the control reference of the acceleration-tracking control system and the control input of the car-following control system.

By defining $F_{\rm req} = \delta m_v a_{\rm req} + \frac{1}{2} C_D A \rho v^2 + m_v g(f\cos(\alpha) + \sin(\alpha))$ and $e = a_{\rm req} - a_v$, the control law of the traction control for the acceleration-tracking control system is obtained as

$$\begin{cases} T_e^* &= F_{\rm req}\frac{r_w}{\eta_t I_0 I_g} + k_{p0}(e)e + k_{i0}(e)\int e{\rm d}t, \\ P_b^* &= 0, \end{cases} \tag{1}$$

and the control law of the brake control is

$$\begin{cases} P_b^* &= -F_{\rm req}\frac{r_w}{K_b} + k_{p1}(e)e + k_{i1}(e)\int e{\rm d}t, \\ T_e^* &= 0, \end{cases} \tag{2}$$

where δ is the lumped rotational inertial coefficient, m_v is the mass of the vehicle, $a_{\rm req}$ is the desired longitudinal acceleration, a_v is the longitudinal acceleration of the vehicle, r_w is the wheel radius, T_e is the engine torque, P_b is the braking pressure, K_b is the brake system gain, f is the rolling resistance coefficient, C_D is the aerodynamic drag coefficient, A is the frontal area, ρ is the air density, v is the vehicle speed, g is the gravity constant, I_0 is the conversion ratio of final gears, η_t is the mechanical transmission efficiency, and I_g is the discrete gear ratio. The slope angle α is estimated by a filter [8] in the vehicle start-up phase. For other phases in the stop-and-go scenarios, the slope angle is obtained from the HD map.

The controller gains of the engine torque $k_{p0}(e)$, $k_{i0}(e)$ and those of the brake pressure $k_{p1}(e)$, $k_{i1}(e)$ are error-dependent. Therefore, the feedback parts are two gain-scheduled PI controllers.

Indeed, gear ratio I_g is an input variable in many researches to explore more energy-saving potential. The vehicle under investigation is a sport utility vehicle with 6-speed automatic transmission (AT). The AT system's gear-shifting control permissions are not open for us. Therefore, gear ratio I_g is not an input variable. In this study, a well-developed gear shift-map is used to determine an appropriate gear ratio for the AT system.

Road intersection information. Given that the vehicle will decelerate when arriving at the traffic light intersection, road intersection information is introduced into the proposed control system as a speed constraint. This speed constraint varies with the distance to the intersection. A predefined constraint profile is used in the real vehicle implementation to ensure a gentle deceleration.

Efficient lookup table algorithm. The considerable computational burden restricts the application of MPC in real vehicles. The prediction of system states is one of the main time-consuming operations. All the HD map data are stored in dynamic maps; thus every prediction of the system states requires multiple lookup table operations. HD map-based MPC needs to perform a large number of lookup table operations in the prediction horizon. Therefore, an efficient lookup table algorithm is proposed to reduce the computational complexity of the predictive model.

The predictive upcoming vehicle location is steadily increasing because the vehicle speed is non-negative in the prediction horizon. Given the advantage of this characteristic, an improved lookup table algorithm is proposed for the HD map-based MPC. This algorithm is backward traversal and begins with the current vehicle location. We only need to compare the target location with a one-dimensional (index) sequence. Once matched, the table searching is done. In a same prediction horizon, the next table searching begins from the last searched index.

Experimental results. Road experiments were conducted on a real vehicle experimental platform to evaluate the energy saving performance of the proposed longitudinal driving strategy. Further details about this platform are presented in [7]. The test roads are composed of sections of Chongqing and Wuhan. The total test mileage is approximately 1750 km. The benchmark controller is a factory-installed adaptive cruise control system.

To evaluate the influence of road slope signal on the energy saving performance, comparative experiments are performed with and without the signal. Comparison tests against the human drivers are also performed.

Conclusion. The study presents an energy-efficient longitudinal driving strategy with the stop and go function. After introducing the design of the stop-and-go controller, the use of road intersection information is presented. Thereafter, an efficient look-up table algorithm is proposed to reduce the computational complexity in the predictive horizon. Finally, experimental results evaluate the performance of the proposed longitudinal driving strategy.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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