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Fuel Economy Assessment of MPC-ACC on Powertrain Testbed

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Abstract. The development and testing of Advanced Driver Assistance Systems (ADAS) is one of the most active fields in the automotive industry towards Automated Driving (AD). This work presents the deployment and testing of an Adaptive Cruise Control (ACC) based on Model Predictive Control (MPC). The goal is to design and validate through the experimental campaign a computationally efficient longitudinal dynamics controller and assess its fuel economy potential. The development of the control structure as well as the definition of the testing method for energy efficiency assessment are central aspects of this work. The performance of the approach is tested on a light-duty commercial vehicle on a state-of-the-art 4-axis powertrain testbed. The findings demonstrate that the speed profile can be optimized to achieve a fuel reduction of up to 13% while maintaining mission timing and comfort.

Keywords: Advanced Driver Assistance Systems · Adaptive Cruise Control · Model Predictive Control · 4-axis powertrain testbed

1 Introduction to ADAS for Fuel Economy

In the past decades, vehicles have been increasingly equipped with connectivity and automation technologies with the introduction of communication infrastructures and onboard sensors [1]. Compared to manual driving, vehicles equipped with Advanced Driver Assistance Systems (ADAS) can be controlled more precisely, improving road safety and traffic flow stability [2]. In recent years, there has been a marked interest in using ADAS beyond safety and comfort to also address vehicle efficiency improvement [3].

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Adaptive cruise control (ACC) is one of the most popular ADAS available on a wide variety of mass-production vehicles. ACC has proven to be well-suited to enhance fuel economy because of the possibilities opened by prescribing a target lead vehicle speed [4]. A wide variety of strategies have been proposed to minimize fuel consumption, especially when the following policy is solved under a predictive control framework [5–7]. Recent literature on the topic only partially focuses on systematic assessment of energy savings from ADAS with experimental testing [8], while great attention is paid to the impact of low-level control policies on stability [9].

This work presents a novel experimental framework to assess fuel economy improvement introduced by a predictive controller deployed in real-time and tested in a powertrain testbed. The proposed ACC sets the optimal target acceleration to guarantee passenger comfort and reduce fuel consumption. Special attention is paid to a low-level controller to guarantee a good enough tracking of the desired acceleration. Experimental results demonstrate fuel consumption reduction up to 13% especially when relaxed headway time values are set.

The work is organized as follows. Section 2 presents the proposed ACC controller, the MPC problem formulation, and the inner feedforward-feedback acceleration tracking controller. Section 3 concludes with the ACC real implementation on powertrain testbed.

2 Adaptive Cruise Control on Powertrain Testbed

The proposed ACC is implemented on a vehicle installed in a powertrain testbed (hereinafter called host vehicle) as depicted in Fig. 1.

The lead vehicle speed profile is emulated together with the host vehicle radar to properly generate the relative distance and relative speed profiles. The high-level predictive controller uses kinematic vehicle constraints to determine the optimal target acceleration for the host vehicle. Then, a low-level controller with combined feedback and feedforward action properly tracks the given reference. The powertrain testbed automation system made it possible to conduct a systematic assessment of vehicle performance.

In the following, the two proposed control layers are briefly described.

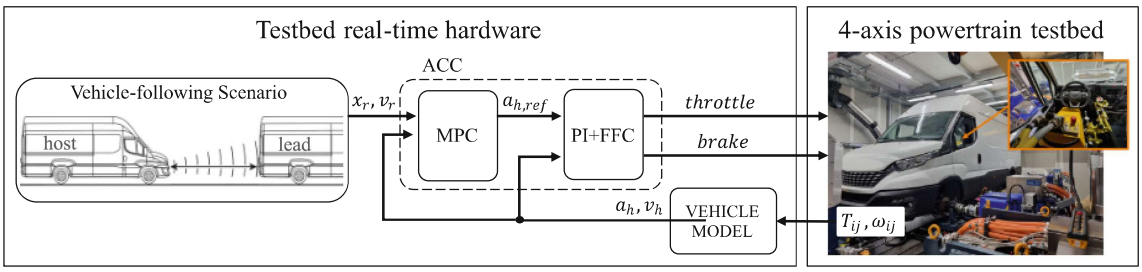


Fig. 1. Scheme of the experimental framework on the 4-axis powertrain testbed in which the MPC-ACC has been tested.

2.1 MPC Controller Design

Assuming that the low-level control action ensures perfect tracking of the desired acceleration $a_{h,ref}(t)$, it can be modeled together with the internal vehicle dynamics as a single integrator. In this way, the host vehicle speed $v_h(t)$ is related to the desired acceleration $a_{h,ref}(t)$ with the following set of equations [10]:

$$\begin{cases} x_r(t) = x_r(0) + \int_{t_0}^{t} v_r(t)dt \\ v_r(t) = v_r(0) + \int_{t_0}^{t} a_r(t)dt \\ v_h(t) = v_h(0) + \int_{t_0}^{t} a_h(t)dt \end{cases} \tag{1}$$

where $x_r(t)$ is the relative position between the lead and the host vehicle, $v_r(t) = v_l(t) - v_h(t)$ the relative velocity, $a_r(t) = a_l(t) - a_h(t)$ the relative acceleration, $v_h(t)$ the host vehicle velocity, and $a_h(t)$ the host vehicle acceleration at time t. The values of $x_r(t)$ and $v_r(t)$ are given by the radar, and the host vehicle speed $v_h(t)$ is assumed available in vehicle control unit. The relative acceleration becomes $a_r(t) \equiv -a_h(t)$, as the acceleration of the lead vehicle $a_l(t)$ is unknown, and assumed to be zero for the prediction model. The host vehicle acceleration $a_h(t)$ is used as a control decision variable, and $a_l(t)$ acts as a disturbance on the system.

In ACC, an important performance parameter is the desired headway time ($t_{hw,d}$) i.e., a way for the driver to communicate how closely the vehicle should follow the preceding one. The desired headway time is used to define a reference distance

$$x_{r,d}(k) = x_{r,0} + \bar{v}_h(k)t_{hw,d} \tag{2}$$

that depends on a constant $x_{r,0}$, representing the minimum distance, and the host vehicle's speed v_h. The latter is saturated as:

$$\bar{v}_h(k) = \begin{cases} v_h(k) & \text{if } v_h(k) < V_{\max} \\ V_{\max} & \text{if } v_h(k) \geq V_{\max} \end{cases}$$

where $V_{\max}$ is the road limit speed.

Correspondingly, the tracking error at time step k is defined as $e(k) = x_{r,d}(k) - x_r(k)$. Hence, a primary control objective is minimizing the absolute tracking error $e(k)$.

Constraints related to safety and comfort are detailed in the following:

- ***Safety***: the inter-vehicle distance should always be greater than a minimum safe distance, i.e. $x_r > x_{r,\min}$, thus avoiding collisions. Furthermore, the relative velocity between the vehicles should be minimized, $|v_r(k)|$.
- ***Comfort***: the peak values of the host vehicle acceleration $|a_h(k)|$ and jerk $|j_h(k)|$ should be kept small to guarantee the comfort of driving action. To accommodate the jerk constraints into the MPC problem, the host acceleration is written as a state, and its variation

$$\frac{da_h}{dt} \equiv j_h(t) \equiv u(t)$$

is treated as an input u, which written in discrete-time domain becomes

$$a_h(k) = a_h(k-1) + T_s u(k) \tag{3}$$

The proposed MPC-ACC needs a dynamic model to predict the evolution of the vehicle and its surroundings. To do that, the equations in (1) are firstly written in discrete-time domain with sample time T_s and then combined with (3) to obtain a discrete-time state space model:

$$\xi(k+1) = A\xi(k) + Bu(k) \tag{4}$$

with states $\xi = [x_r(k),\ v_r(k),\ v_h(k),\ a_h(k-1)]^\top$, and matrices

$$A = \begin{pmatrix} 1 & T_s & 0 & -\frac{1}{2}T_s^2 \\ 0 & 1 & 0 & -T_s \\ 0 & 0 & 1 & T_s \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ 0 \\ 0 \\ T_s \end{pmatrix}. \tag{5}$$

The following MPC problem is proposed for the ACC:

$$\min_{\xi,u} \sum_{k=1}^{N} ||\xi_k - \xi_k^{ref}||_{\mathbf{Q}}^2 + ||u_k||_R^2 \tag{6a}$$

subj. to

$$\xi_{k+1} = A\xi_k + B\delta u_k \quad k = 0, \ldots, N-1 \tag{6b}$$

$$x_{r,\min} < x_r(k) \tag{6c}$$

$$a_{h,\min} \leq a_h(k) \leq a_{h,\max}\left(v_h(k)\right), k \in N \tag{6d}$$

$$|u(k)| \leq j_{h,\max}. \tag{6e}$$

Weight matrix $Q \succeq 0$ is properly set to track the relative distance with the minimum effort in terms of acceleration, while $R \succ 0$ is tuned to normalize the variations of the acceleration with the state deviations. Constraints on relative distance, acceleration, and jerk are set to guarantee comfort. Hence, the controller tries to properly follow the lead vehicle with minimum effort in terms of acceleration command. This approach produces a smoother speed profile, which indirectly reduces fuel consumption and improves comfort.

The resulting control problem (6) is cast into a quadratic programming (QP) problem once and offline. At each time step, the problem is updated with the current state and then solved to obtain the optimal acceleration deviation $u^*(t)$. Finally, the target acceleration is updated using Eq. (3) and set as the new reference for the inner acceleration control layer, as explained in Subsect. 2.2. The proposed method allows real-time implementation on the testbed's hardware. It is worth mentioning that, to avoid infeasibility issues, a slack variable is added to the acceleration state constraints. During the implementation, its activation has been noticed only in critical conditions, like panic braking of the lead vehicle or when running on aggressive driving cycles.

2.2 Low-Level Acceleration Tracking Control

The low-level controller generates accelerator and brake pedal signals to accurately track the target acceleration $a_{h,ref}$. It combines a feedforward (FFC) and a feedback (FBC) controller. The FFC generates throttle and braking commands by inverting the vehicle model. The FBC, which uses a PI (Proportional-Integral controller), compensates for plant-model mismatches by tracking the speed reference $v_{h,ref}$ generated from the integration of $a_{h,ref}$. For the sake of brevity, this work excludes all calibration details and instead presents a simplified control scheme, as depicted in Fig. 2. Note that the information about the actual gear and road grade (RG) profile is used by the feedforward to guarantee a better plant model inversion and hence improve the open-loop tracking of the desired vehicle acceleration.

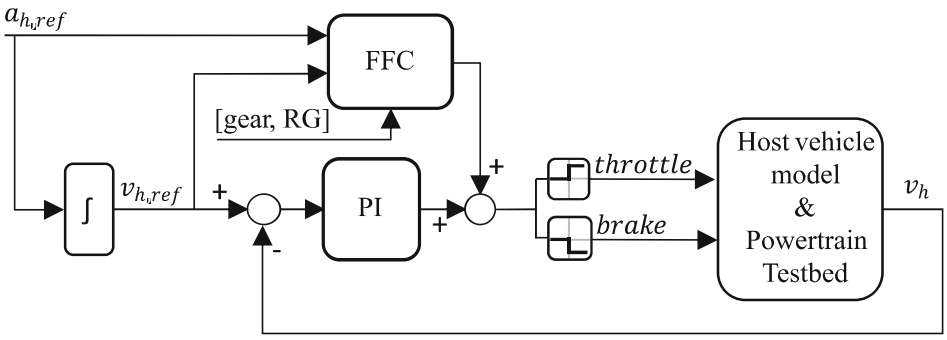


Fig. 2. Simplified low-level controller scheme.

3 Experimental Results and Conclusions

The proposed MPC-ACC is evaluated at a vehicle level in the powertrain testbed. This setup enables a systematic assessment of the fuel consumption in repeatable conditions over different driving cycles by directly measuring the fuel rate of the internal combustion engine. Experimental results obtained on a 2.5-ton light-duty commercial vehicle are reported in Table 1.

Table 1. Fuel Consumption (FC) reduction achieved by the MPC-ACC with 3 s headway time. The results are mean values of FC with dispersion, obtained by giving the host and lead speed profiles references 3 times to the same driver model, thus allowing the assessment of different vehicle responses to the same speed profiles.

Scenario	Lead FC [L]	Host FC [L]	FC Reduction [%]
Urban	1.30 ± 0.01	1.14 ± 0.01	13.5 ± 0.1
Extra-urban	3.82 ± 0.02	3.32 ± 0.01	13.0 ± 0.3
Highway	5.54 ± 0.02	5.40 ± 0.01	2.6 ± 0.2

The difference in fuel consumption is evaluated by giving the lead and the host speed profiles to the same vehicle under test. The speed profiles and fuel consumption in both cases are reported in Fig. 3. The results show that by adopting a headway time of 3 seconds, the proposed MPC-ACC can improve fuel consumption by up to 13% in urban and mixed extra-urban driving scenarios while respecting mission timing. Minor effects on fuel economy have been highlighted in highway scenarios, where well-known state-of-the-art techniques remain more suitable.

The results have demonstrated the promising application of Vehicle-in-the-Loop (ViL) testing on a 4-axis powertrain testbed. Future works will use cutting-edge hardware stimulators to replace emulated radar and camera with real data from the vehicle's onboard sensors.

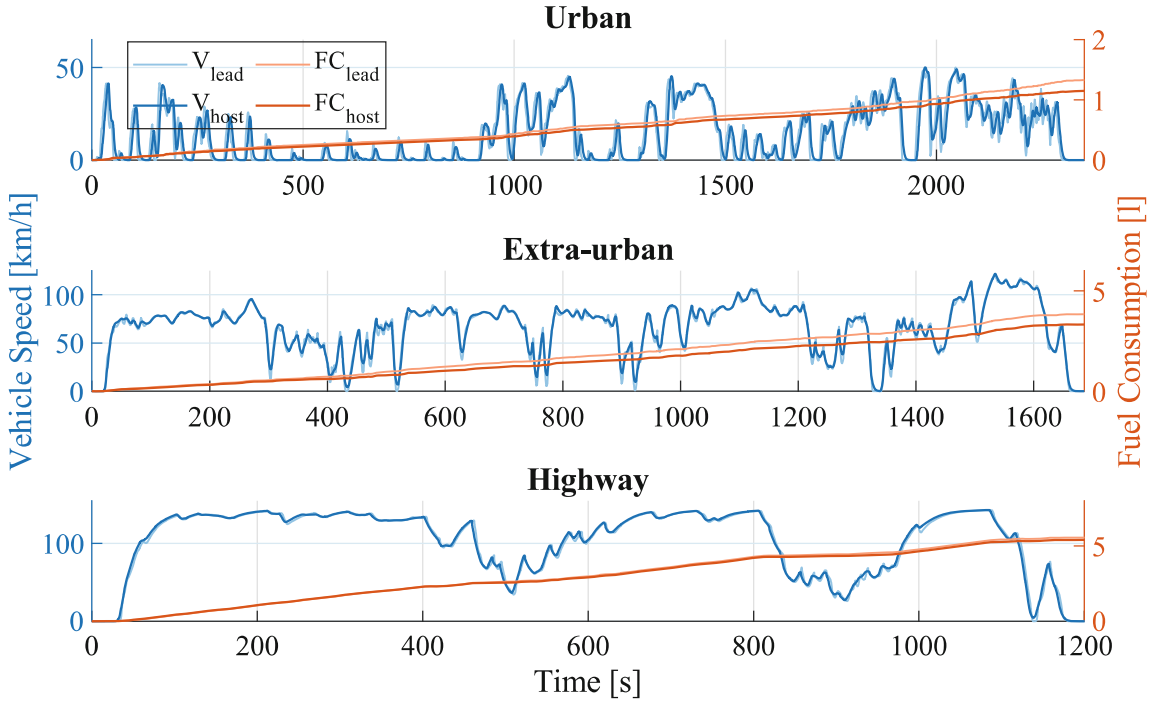


Fig. 3. Fuel consumption results of the MPC-ACC on Real-Driving Emissions (RDE) profiles, i.e. RDE Urban (top), RDE Rural (center), and RDE Motorway (bottom). The host and lead speed profiles are performed by the same vehicle, namely the light-duty commercial vehicle, to highlight the potential fuel consumption reduction.

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