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IFAC PapersOnLine 52-5 (2019) 21–27

# Adaptive Cruise Control Strategies Implemented on Experimental Vehicles: A Review

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**Abstract:** It has been over two decades since the first generation of adaptive cruise control (ACC) equipped vehicles were launched onto the market. However, control strategies adopted by commercially available ACC systems are the closely-guarded intellectual property of their industrial developers, so these are not publicly available and there is no uniform standard for ACC dynamic response. However, the impact of ACC dynamics on transport networks needs to be studied. In the open literature, there are many ACC systems published and embedded in simulation studies, nevertheless, inappropriate model design can easily point to misleading conclusions. Only a few projects dealing with automated systems are founded on real experimental data, which is important for developing precise ACC models and furthermore, evaluating their realistic effects on highway capacity and traffic flow dynamics. This review firstly summarizes the available literature on control strategies for ACC systems implemented on experimental vehicles, then propose a five-layer framework for the development and evaluation of ACC or CACC control strategies based on future trends.



*Keywords:* Adaptive Cruise Control, Vehicle Dynamics, Connected and Autonomous Vehicles, Intelligent Transportation Systems, Multi-objective Optimization

## 1. INTRODUCTION

Nowadays, transportation and automotive industries in the world face significant challenges. Firstly, limited road infrastructure capacity is one of the primary reasons for congestion in large cities (Schrank et al., 2012). Secondly, driver error has been considered as the leading cause of most roadway crashes (Iden et al., 2006). Thirdly, new legislation set more stringent targets to reduce vehicle emissions (Martinez et al., 2017), for example, European Commission adopted the proposed target for average $CO_2$ emissions from new heavy-duty vehicles in 2030, at least 30 % lower than in 2019 (European Commission, 2019). Finally, a more sustainable transport system calls for eco-driving styles to reduce fuel consumption (Andrieu et al., 2012). However, along with these challenges comes the opportunities for intelligent transportation systems (ITSs) and connected & autonomous vehicles (CAVs) (Ye et al., 2018). Among the most critical automated functionalities, adaptive cruise control (ACC) is a commercially available vehicle longitudinal control system, which could potentially contribute to addressing challenges mentioned above (Dey et al., 2016).

It has been over two decades since the first generation of ACC equipped vehicles were launched onto the market (Xiao et al., 2010). Detailed control strategies adopted by commercially available ACC systems are the closely-guarded intellectual property of their industrial developers and not publicly available (Milanés et al., 2014). Moreover, there is no uniform standard for ACC dynamic response, i.e., ACC systems from different manufacturers show a significant diversity of dynamic responses, depending on the limitations of sensors implemented, and performance objectives matched with personalities of their host vehicles (Shladover et al., 2012).

The first system introduced onto the market, which can actively control the vehicle speed independent of driver actions, is conventional cruise control (CCC) allowing a vehicle to drive at a certain speed by regulating the throttle position (Shaout et al., 1997). Its speed can be set via the driver interface. The second stage in the development of vehicle longitudinal control system was adaptive cruise control (ACC), belonging to Level 1 automation as defined by both SAE and NHTSA (Shladover et al., 2015). With sensors such as radar, lidar and camera, ACC enables the host vehicle to detect the vehicle ahead and adapt its longitudinal speed to the preceding one in keeping with a pre-selected gap. Thus, both brake and throttle action is done automatically (Serafin, 1996). Many distance regulation policies have been proposed (Zhou et al., 2005), e.g.,

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10.1016/j.ifacol.2019.09.004

constant spacing policy (Shladover, 1995) and constant (time) headway policy (Xiao et al., 2011), which have considerable influence on the individual vehicle stability (Swaroop et al., 1994), string stability (Liang et al., 1999), traffic flow stability (Arem et al., 2006), etc. Stop & Go Cruise Control can be regarded as a more sophisticated variant of ACC with the capability of automatic start and stop, tracking the preceding vehicle at low-speed driving and increasing the driver comfort especially in congested traffic (Piao et al., 2008).

With the advent of vehicle-to-vehicle (V2V) communications such as DSRC (Willke et al., 2009), the next generation of the automatic longitudinal control system is cooperative adaptive cruise control (CACC). Based on conventional ACC sensors and wireless V2V communication links, a CACC system can obtain more extensive preceding vehicle information, allowing for the inter-vehicle distance significantly smaller than those of ACC or manual driving (Shladover et al., 2010) and thus, greatly increasing the road throughput (Ploeg et al., 2011). However, wireless communication links also introduce new dynamic subsystems into the control loops (Xu et al., 2014). Consequently, new challenges may arise due to communication uncertainties (Freudenberg et al., 2008; Rogelioluck et al., 1994), e.g., time delay, packet loss and errors, which may severely deteriorate the driving safety. On the other hand, the information structure (e.g., connected with the preceding vehicle only, or connected with multiple preceding ones), information content (distance, speed, or early warning of the driver's braking action) and data fusion also should be taken into consideration when designing control strategies for CACC (Xu et al., 2014). CACC is currently under development and may drastically change the way we travel in the decades to come (Shladover et al., 2012).

Most of ACC systems published in the open literature are developed in simulation studies, however, inappropriate model design can easily point to misleading conclusions (Makridis et al., 2018). Only a few projects dealing with automated systems are founded on real experimental data, which is vital for developing accurate ACC and furthermore, evaluating their realistic effects on highway capacity and traffic flow dynamics in microscopic simulations. Considering the shortage of public documentation of control approaches of real ACC equipped vehicles, and the variety of ACC driving behaviour, this paper reviews the literature on adaptive cruise control strategies implemented on experimental vehicles, the remainder of which is arranged as follows. Section 2 gives a comprehensive analysis of available projects on ACC systems implemented on experimental vehicles. Section 3 summarizes the strengths and weakness of their control strategies, followed by proposing an innovative five-layer framework for the development and evaluation of the ACC/CACC control strategy, in terms of its interaction with powertrain, vehicle, fleet, traffic and infrastructure. Conclusions are summarized in Section 4.

## 2. EXPERIMENTAL IMPLEMENTATION OF ACC CONTROL STRATEGIES

Only a few studies investigate ACC control strategies based on real experimental data, which is essential to develop accurate models of the dynamic responses of ACC systems and to produce realistic predictions of their effects on highway capacity and traffic flow dynamics. This section will describe some designs of control strategies for ACC systems implemented on experimental vehicles.

### *2.1 PID Feedback/Feedforward Control*

The PID controller is commonly used in real industrial control systems. It consists of three basic terms, i.e., proportional term, integral term and derivative term. Three corresponding coefficients are varied in each PID controller to get the optimal response. CASE 1 & 2 are examples using PID feedback/feedforward control in prototype ACC systems (Ioannou et al., 1993).

CASE 1

Shladover et al. (Milanés et al., 2014) developed models for both ACC and CACC systems based on experimental data from a field test of production vehicles. Thus, cruise behaviours of these systems are assessed in realistic traffic circumstances and their associated mathematic models can be derived.

To examine the control strategy of the CACC system, a simplified controller model is used. The distance error $e$, i.e., the error of actual distance $\Delta x$ and desired distance $\Delta x_d$, and its derivative $\dot{e}$ are applied to determine the following vehicle speed:

$$\begin{aligned} v_f(t) &= v_f(t-t_s) + k_p e(t-t_s) + k_d \dot{e}(t-t_s) \\ e(t-t_s) &= \Delta x(t-t_s) - t_{hw,d} v_f(t-t_s) \end{aligned} \tag{1}$$

where $t_s$ is the sampling time, $k_p$ and $k_d$ are coefficients for proportional and derivative terms, respectively.

To model the behaviours of commercially available ACC controller, acceleration of the following vehicle $a_f(t)$ is expressed as a function of the distance error $e$ and the relative speed $\Delta v$:

$$\begin{aligned} a_f(t) &= k_{p1} e(t-t_s) + k_{p2} \Delta v(t-t_s) \\ e(t-t_s) &= \Delta x(t-t_s) - t_{hw} v_f(t-t_s) \end{aligned} \tag{2}$$

where $k_{p1}$ and $k_{p2}$ are coefficients for two proportional terms.

CASE 2

In Grand Cooperative Driving Challenge (GCDC), Lidstrom (Lidstrom et al., 2012), Nieuwenhuijze (Nieuwenhuijze et al., 2012) and Guvenc (Guvenc et al., 2012) also used proportional, or proportional-derivative feedback/feedforward control to design longitudinal speed control systems for production vehicles. In their functional architectures, the developed control system performed three tasks: 1) sensing task – perceiving states of the surrounding environment and the host vehicle; 2) data fusion task –

combining the data from different sensors to mitigate the sensor inaccuracies; 3) control task – generating the acceleration command using improved states estimation.

Within the production vehicle used for field tests, the lower-level controller gives input signals to powertrain components, e.g., internal combustion engine, electric motor and braking system, to track the desired acceleration $a_{f,d}$ , of which the Laplace transformation is $A_{f,d}(s)$ . By evaluating the frequency response function (FRF) on a dynamometer, dynamics of the vehicle and its lower-level controller can be described as a third-order model with a time lag $\tau_l$ and an actuation delay $\tau_d$ :

$$G_f(s) = \frac{X_f(s)}{A_{f,d}(s)} = \frac{1}{s^2(\tau_l s+1)} e^{-\tau_d s} \tag{3}$$

As illustrated in Fig. 1, the control structure of the upper-level controller (ACC or CACC system) is composed of two parts: 1) feedforward part using the acceleration of the leading and/or preceding vehicle as inputs; 2) feedback part using the actual distance $\Delta x$ and the distance error $e$ as inputs.

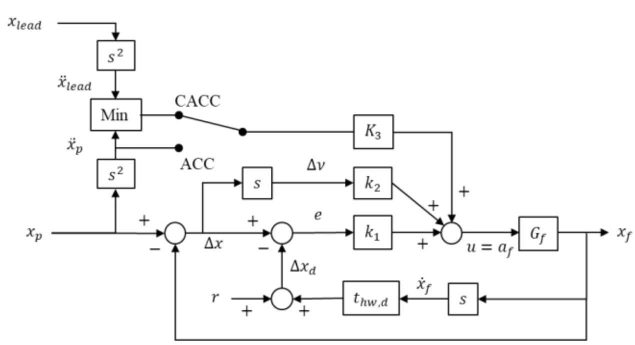



Fig. 1. Proportional-derivative feedback/feedforward control structure for ACC and CACC (Lidstrom et al., 2012).

The feedforward controller is a filter $K_3$, designed to achieve string stability according to the acceleration of leading and/or preceding vehicle. It is parametrized as:

$$K_3(s) = \frac{k_3 + k_4 s}{1+\tau_f s} \tag{4}$$

where $k_3$ and $k_4$ are proportional and derivative coefficients, respectively. It is used to diminish the effect of noise. Feedforward part is based on the acceleration of preceding and/or leading vehicle, the reason of which is to avoid overreacting on the hard acceleration or deceleration, and thus ensure safety. This control strategy could prevent the risk of coming too close to the vehicle ahead.

The feedback controller is used to minimize the distance error and relative speed via proportional control terms.

The transfer function for the whole system of an ACC equipped vehicle, including the lower-level part (vehicle and its lower-level controllers) and upper-level part (ACC controller), can be described as ( $r=0$ ):

$$X_f(s) = \frac{[k_1 + sk_2 + s^2 K_3]G(s)}{1+[k_1(1+t_{hw,d}) + sk_2]G(s)} X_p(s) \tag{5}$$

When switching to CACC ( $r \neq 0$ ), accelerations of leading and preceding vehicles are both considered in the feedforward part. The transfer function for the whole system is:

$$\begin{aligned} A_p(s) &= \min\{s^2 X_p(s), s^2 X_{lead}(s)\} \\ X_f(s) &= \frac{[K_3 A_p(s)s + (k_2 s^2 + k_1 s)X_p(s) - k_1 r]G(s)}{s+[k_1(s+t_{hw}s^2)+k_2 s^2]G(s)} \end{aligned} \tag{6}$$

## 2.2 Model Predictive Control (MPC)

The distinguishing feature of MPC is calculating the current control action by solving an online, iterative and finite-horizon optimization of the plant model. Fig. 2 illustrates an MPC control scheme for ACC systems (Li et al., 2011). MPC procedures include: 1) predicting future system states based on current states; 2) computing the cost function for a finite time horizon in the future; 3) implementing the first step of the solved control sequence; 4) applying the feedback control loop to compensate for the predictive error and model inaccuracy; 5) sampling new current plant states and repeating the above process. CASE 3 is an example of prototype ACC systems based on MPC methods.

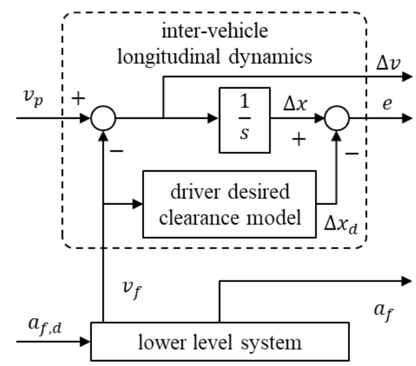



Fig. 2. An MPC scheme for ACC systems (Li et al., 2011).

CASE 3

Geiger et al. (Geiger et al., 2012) designed a CACC system for an experimental vehicle, based on model predictive control strategy. This is achieved by employing a nonlinear kinematic model assuming the preceding vehicle will drive at constant yaw rate and acceleration, up to the time horizon T (currently 10 seconds). To determine the optimal control command (i.e., desired acceleration of the following vehicle), the cost function, integrating a weighted sum of squares of three terms, is minimized:

$$\begin{aligned} J(u) &= \int_{t_0}^{t_0+T} w_e e(t)^2 + w_a u(t)^2 + w_v \Delta v(t)^2 dt \\ e(t) &= \Delta x(t) - (r + t_{hw} v_f(t)) \\ \Delta v(t) &= v_p(t) - v_f(t) \\ u(t) &= a_f(t) \end{aligned} \tag{7}$$

where $w_e$, $w_a$ and $w_v$ are weighting factors for targets of reducing the distance error, penalizing the excessive acceleration and diminishing the relative speed, respectively. $r$ is the desired distance at standstill, and the control output $u(t)$ is the acceleration of the following vehicle.

### 2.3 Fuzzy Logic Control (FLC)

Compared with ACC systems, Stop & Go systems are often designed: 1) for lower velocity (< 40 km/h); 2) with smaller deceleration; 3) requiring better object detection sensors. In the following case, FLC has been applied to achieve both functions of ACC and Stop & Go systems in a unified control framework (Naranjo et al., 2003).

CASE 4

Tsai et al. (Tsai et al., 2010) proposed a longitudinal speed control system (ranging from 0 to 120 km/h) by integrating ACC and Stop & Go control based on fuzzy logic method. With two inputs, i.e., distance error $e$ and relative speed $\Delta v$, the unified controller gives the pulse-width-modulation (PWM) output command to determine the throttle position and braking pressure. With MicroAutoBox (provided by dSPACE) and Matlab/Simulink, the fuzzy controller can be implemented on the experimental vehicle.

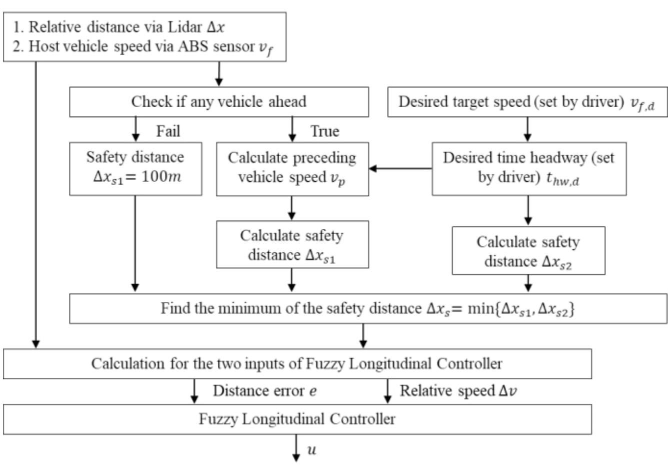
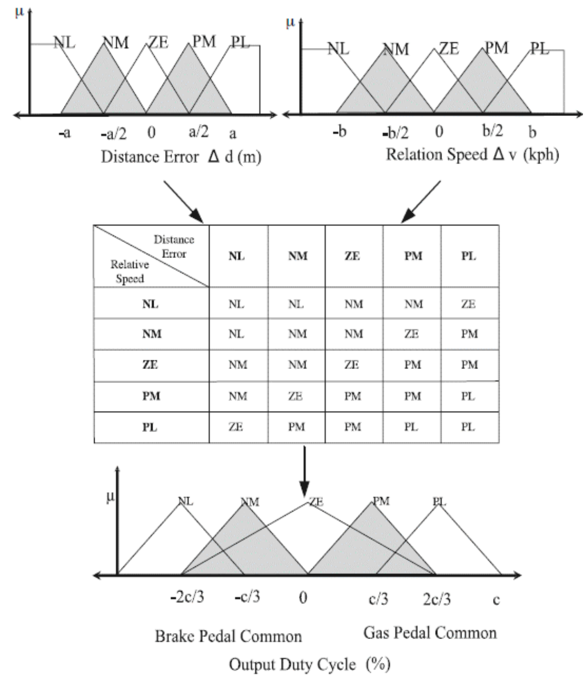



Fig. 3. The architecture of the proposed fuzzy longitudinal controller (Tsai et al., 2010).

Fig. 3 illustrations the flowchart of the proposed controller. There are three conditions to calculate the safety distance: 1) when a preceding vehicle is detected via the sensor, the safe distance $\Delta x_{s1}$ should be estimated based on the preceding vehicle speed $v_p$ and the driver desired time headway $t_{hw,d}$; 2) when no preceding vehicle is sensed, the safety distance $\Delta x_{s1}$ is set to be 100 m; 3) when the driver has specified the desired time headway $t_{hw,d}$ and speed $v_{f,d}$, the safety distance $\Delta x_{s2}$ is their product. The final safety distance is defined as $\Delta x_s = \min\{\Delta x_{s1}, \Delta x_{s2}\}$.

Fig. 4 shows fuzzy sets and the rule matrix of the controller. For simplification, the triangular membership functions are chosen to fuzzy two inputs (distance error $e$ and relative speed $\Delta v$) and the output (desired acceleration $a_{f,d}$) into five linguistic variables, i.e., 'negative large' (NL), 'negative medium' (NM), 'near zero' (ZE), 'positive medium' (PM) and 'positive large' (PL).




| Relative Speed \ Distance Error | NL | NM | ZE | PM | PL |
|---|---|---|---|---|---|
| NL | NL | NL | NM | NM | ZE |
| NM | NL | NM | NM | ZE | PM |
| ZE | NM | NM | ZE | PM | PM |
| PM | NM | ZE | PM | PM | PL |
| PL | ZE | PM | PM | PL | PL |

Fig. 4. Fuzzy sets and the rule matrix (Tsai et al., 2010)

## 3. OUTLOOK

The previous section analyzes currently available cases of ACC/CACC control strategies implemented on experimental vehicles, including PID feedback/feedforward control, model predictive control (MPC) and fuzzy logic control (FLC). Their advantages, disadvantages and features are summarized in Table 1. The transportation and automotive trends also indicate that to achieve greener, safer, more efficient and stable ACC or CACC systems in the future, their control strategies should be developed and evaluated from perspectives of five different layers:

1) Powertrain layer: the powertrain performance such as fuel economy is strongly affected by power demands from ACC driving systems, e.g., the low-speed driving operation usually leads to higher energy loss for either the internal combustion engine or the electric motor. Thus, it's important for the development of ACC systems to ensure energy and power sources (e.g., the engine and batteries) always work at high efficiency and low emissions operation points (Li et al., 2015). In particular, for hybrid electric vehicles, ACC power demands can be coordinated among multiple power sources, therefore, the associated energy management strategies need to be examined when developing ACC systems (Kural et al., 2015).

Conversely, the driving decision made by ACC systems can also take into account the powertrain capabilities and states such as response time and range limitation etc. For instance, if the electric vehicle is running at a low battery state of charge (SoC), the ACC driving control should tend to gentle deceleration when applicable in order to recycle kinetic energy using the regenerative braking system (Yan et al., 1999).

2) Vehicle layer: the individual vehicle stability with respect to a desired following distance is essential to guarantee the safety and ride comfort (Swaroop et al., 1994). In literature, three steady-state spacing policies are proposed for control implementation (Bageshwar et al., 2004): the constant distance policy, the constant (time) headway policy, and the constant safety factor policy. Control strategies of ACC systems must keep the inter-vehicle distance specified by the spacing policy, regardless of the manoeuvre performed by the immediately preceding vehicle. The fulfilments of these spacing policies depend, however, strongly on the real-time traffic information available to ego ACC system, in terms of the target vehicle and, if applicable, other vehicles preceding the target one.

**Table 1. Advantages, disadvantages and features of ACC control strategies in the case studies.**

| Advantages | Disadvantages | Cases & Features |
|---|---|---|
| • PID control: | | |
| - easy to implement and understand<br>- efficient to use limited onboard power & hardware resources<br>- easy to tune and robust in the presence of unmeasured disturbances | - to balance different coefficients, which may compromise the transient response<br>- generally yielding nonoptimal control in real-life driving conditions | Shladover et al. (Milanés et al., 2014), Grand Cooperative Driving Challenge (GCDC) (Lidstrom et al., 2012; Nieuwenhuijze et al., 2012; Guvenc et al., 2012)<br>- feedforward loop: to avoid overreacting<br>- feedback loop: to minimize the relative speed and distance error |
| • Model predictive control (MPC): | | |
| - easy to achieve precise and optimal control with the future trip information<br>- capable of real-time multi-objective optimal control<br>- able to use information from ITS, GIS, GPS, etc. | - strong dependence on the model accuracy<br>- heavy computational burden<br>- requiring a certain level of future trip information, which is generally not the case in real life | Geiger et al. (Geiger et al., 2012), Li et al. (Li et al., 2011)<br>- multiple objectives, e.g., minimal tracking error, low fuel consumption and accordance with driver characteristics, can be achieved simultaneously |
| • Fuzzy logic control (FLC): | | |
| - to mimic human reasoning behaviours based on linguistic models<br>- dealing with nonlinear, integrated and complex cruise control problem with simple mathematics | - generally yielding nonoptimal control in real-life driving conditions<br>- too many parameters, e.g., number of membership functions, ranges of each function, the shape, the overlap percentages, etc. | Tsai et al. (Tsai et al., 2010)<br>- the function of ACC and Stop & Go can be achieved at the same time, i.e., full speed range |

3) Fleet layer: when multiple ACC equipped vehicles are formed as a fleet and drive close to each other, the string stability is a crucial issue that should be taken into consideration (Zheng et al., 2015). A fleet is string stable only if disturbances (e.g., distance error and relative speed) are not amplified when propagating along the vehicle string (Ploeg, et al., 2014). There are four principal approaches for the development of ACC control strategies, to enhance the fleet string stability: i) to use non-identical controllers with linearly increasing control effort (Khatir et al., 2004), however, which may lead to saturation in the throttle angle input in corresponding vehicles at the tail of the platoon; ii) to adopt predecessor-leader following topology (Seiler et al., 2004), broadcasting the leading vehicle's information to every follower via vehicle-to-vehicle (V2V) communications such as DSRC, where certain time delays will be introduced due to information transmitting; iii) to use the constant time headway spacing policy instead of the constant distance policy, thus increasing the fleet formation flexibility (Xiao et al., 2011); iv) to establish a bidirectional (Ghasemi et al., 2013) or multiple-vehicle look-ahead (Ploeg et al., 2014) information flow topology for ACC control strategies.

4) Traffic layer: considering the impact of ACC equipped vehicles on traffic flow dynamics, adaptive cruise control strategies should ensure the traffic smoothness in shock waves (Arem et al., 2006) caused by merging and lane changing etc. On the other hand, the large-scale ACC deployment should guarantee increased traffic capacity and reduced travel time (Zhou et al., 2005).

5) Infrastructure layer: the ACC control design can take advantage of the emerging intelligent transportation systems

(ITSs) and vehicle-to-infrastructure (V2I) communication, to automatically adapt the vehicle speed to the road infrastructure, including legal speed limits (Shladover et al., 2012), and speed adaptation in curves (Zohdy et al., 2013), at intersections (Yang et al., 2017), at on-ramps (Davis, 2007), etc., while simultaneously minimizing fuel consumption and travel time. This adaptation capability is sometimes called contextual ACC, another major evolution ongoing on the market.

## 4. CONCLUSION

This review examines projects demonstrating ACC systems implemented on experimental vehicles, which is important for developing accurate ACC models and furthermore, assessing their realistic impacts on highway capacity and traffic flow dynamics. It highlights the strengths and weakness of their control strategies including PID feedback/feedforward control, model predictive control (MPC) and fuzzy logic control (FLC). Innovatively, a five-layer framework is proposed for the development and evaluation of the ACC control strategy, in terms of its interaction with powertrain, vehicle, fleet, traffic and infrastructure. In particular, the fast and effective update of hybrid electric powertrain and cruise driving systems will require consistency, collaboration and interoperability. The control design should also provide the ACC vehicle with individual stability and string stability for the sake of safety and ride comfort. The development of the ACC/CACC system is anticipated to substantially increase highway capacity and reduce travel time when the system reaches a moderate to high market penetration. Additionally, contextual ACC, adapting the vehicle speed to road infrastructure, is another critical evolution ongoing the market.

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