Design and analysis of full range adaptive cruise control with integrated collision a voidance strategy

Mullakkal-Babu, Freddy A.; Wang, Meng; Van Arem, Bart; Happee, Riender

DOI
10.1109/ITSC.2016.7795572

Publication date
2016

Document Version
Accepted author manuscript

Published in
Proceedings of the IEEE 19th International Conference on Intelligent Transportation Systems, ITSC 2016

Citation (APA)
Mullakkal-Babu, F. A., Wang, M., Van Arem, B., & Happee, R. (2016). Design and analysis of full range adaptive cruise control with integrated collision a voidance strategy. In R. Rosetti, & D. Wolf (Eds.), *Proceedings of the IEEE 19th International Conference on Intelligent Transportation Systems, ITSC 2016* (pp. 308-315). Article 7795572 Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/ITSC.2016.7795572

DOI published version: 10.1109/ITSC.2016.7795572

Published in: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)

Design and Analysis of Full Range Adaptive Cruise Control with Integrated Collision Avoidance Strategy

Freddy A. Mullakkal-Babu, Meng Wang, Bart van Arem, Riender Happee

[1]***Abstract*—Current Full Range Adaptive Cruise Control (FRACC) systems switch between separate adaptive cruise control and collision avoidance systems. This can lead to jerky responses and discomfort during the transition between the two control modes. We propose a Full Range Adaptive Cruise Control (FRACC) design integrating adaptive cruise control and collision avoidance into a single non-linear mathematical formulation. The proposed FRACC responds to a velocity-error using a sigmoidal function of forward spacing. Mathematical properties of the controller, in particular string stability, are examined. Simulation experiments demonstrate that the controller yields smooth and safe responses in typical highway scenarios, including hard-braking and cut-in scenarios. Results also show a clear advantage of the proposed controller in string stability performance with reference to a state-of-the-art controller.**

I. INTRODUCTION

In recent years, vehicle automation has gained widespread attention. Adaptive Cruise Control (ACC) is one of the earliest vehicle automation systems that adjust throttle and brake to follow lead vehicles with a desired spacing/distance. ACC has been available in high end cars and is increasingly combined with collision avoidance systems to brake effectively in critical situations. ACC is widely recognized for its potential to cut down traffic congestion, road fatalities, and emissions while enhancing driving comfort [1], [2].

ACC systems regulate vehicle speed and spacing. ACC control laws are primarily based on spacing policies that describe the equilibrium speed-gap condition. Policies such as the constant space gap policy [3] and the constant time gap policy [4], [5], [6] regulate the vehicle movement to maintain a constant space and time gap respectively. Dynamic time headway policies [7], [8] and human car following behavior based policies [9] deploy a nonlinear response to the gap and the speed error. These policies are implemented using various approaches like Proportional Integral and Derivative control [10], fuzzy logic [11] and Model Predictive Control [12], [13]. In short, ACC systems have been well-studied and tested.

Despite the wide attention, early ACC systems have a major drawback. They provide insufficient braking in emergency situations and therefore call for driver intervention. This increases the driver's workload and probability for collision due to reaction delay. This drawback is addressed by Full Range ACC (FRACC) systems with collision avoidance. FRACC allow the vehicle to drive without driver intervention over the entire speed range.

Current scientific literature offers only a few control formulations for FRACC. Moon et al. [14] introduced a Multiple Strategy FRACC formulation (MS-FRACC) based on three driving modes. They classified the driving modes into safe, warning and dangerous, using a non-dimensional warning index and the inverse time-to-collision indicator. They used separate control strategies in each of these modes to determine the desired acceleration [14]. Few FRACC formulations use an integrated solution for all the driving modes by combining the collision avoidance scheme within the desired acceleration formula using safety indicators. Additionally, Zhao et al. proposed another FRACC [15] based on supervised adaptive dynamic programming. All these FRACC controllers were shown to display the capability to safely handle the longitudinal control over the entire speed range.

Despite the demonstrated ability of FRACC systems to safely handle longitudinal control, the collision avoidance schemes used by them lead to some limitations. Firstly, the use of separate control strategies based on deterministic driving modes for collision avoidance can lead to discontinuous accelerations [15] and high deceleration values in emergency scenarios. Secondly, common safety indicators like the inverse time to collision and safe stopping distance [14], [16] produce large jerks or abrupt acceleration fluctuations, particularly in situations characterized by a sudden reduction in space gap, e.g. when a vehicle cuts in ahead. Finally, the performance of these controllers in a vehicle platoon has not been tested. This means that the impact of these controllers on traffic flow, in particular on flow stability and capacity are not yet understood [4], [7]. In short, additional research is needed for FRACC to smoothly handle critical scenarios and to gain insight into their impact on traffic flow if deployed in multiple vehicles forming organized or spontaneous platoons.

The present work proposes a controller design to overcome the limitations of existing FRACC systems. The objective of this paper is to propose a Full Range ACC design that smoothly and safely handles the longitudinal driving task unaided by the human driver and that offers an improved platoon performance compared to a state of the art controller. To this end, the design implements a non-linear control formulation with integrated collision avoidance. The

[1] Freddy A. Mullakkal-Babu, Meng Wang and Bart van Arem are with the Department of Transport & Planning, Fac. Civil Engineering and Geosciences, TU Delft, P.O. Box 5048, 2600 GA Delft, The Netherlands. (corresponding author e-mail: F.A.MullakkalBabu@ tudelft.nl).

Riender Happee is with the Department of Biomechanical Engineering, Fac. Mechanical Maritime and Materials Engineering, TU Delft, Mekelweg 2, 2628 CD, Delft, The Netherlands

proposed FRACC responds to a velocity-error using a sigmoidal function of forward spacing. Mathematical properties of the controller, in particular string stability, are examined. The individual and string performance of the controller is demonstrated in representative scenario simulations with reference to a state-of-the-art controller.

The remainder of the paper is structured as follows. The controller design is detailed in Section 2. The mathematical properties of the controller are investigated in Section 3. Following this, the experimental design to evaluate the controller is described in Section 4. Section 5 presents the experimental results and finally, the conclusions are presented in section 6.

II. FULL RANGE ACC DESIGN

In this section, we present the full range ACC design in terms of the design specifications and control formulation.

A. Design Specifications

Highway driving typically involves two main modes of longitudinal control: free/unconstrained driving and car following. In the free driving mode, the controller should regulate the vehicle velocity to a desired velocity v_0. In the car following mode, the system should regulate acceleration to maintain a time gap, avoid rear-end collisions and regulate the space gap with the preceding vehicle to a value not less than the minimum space gap, s_0. Hence, the control policy should facilitate operation in both of these driving modes.

The control design should yield technically feasible desired acceleration signals and preferably, its performance should meet additional operational specifications: resilient to fluctuations in velocity and spacing errors caused by maneuvers of the leading vehicle like cutting in, cutting out, braking and accelerating; yield continuous desired acceleration signals and operate with a time gap range of (not restricted to) 0.8-2.2 s, which is typically observed in human drivers [17]; it should be locally stable and analyzed for string stability properties to understand the potential impacts on traffic flow.

Fig. 1 depicts the closed loop system with the proposed FRACC. The upper level controller, which is the proposed FRACC controller, computes the desired acceleration (u_n) signal based on the error in spacing and the velocity. Following this, the lower level controller realizes the desired acceleration signal with a lag. Finally, the updated error signal is fed back to the upper level controller.

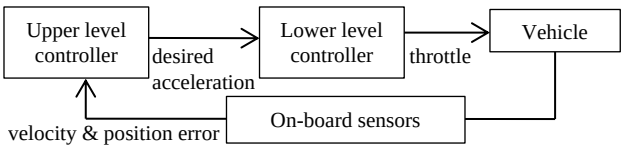

Figure 1. FRACC system framework.

B. Desired Acceleration

The closed loop formulation of the desired acceleration signal as shown in Fig. 1 uses the system state X of FRACC vehicle n, described by its forward space gap s_n; its speed v_n as shown in (1). The relative speed with respect to the preceding vehicle is denoted by $\Delta v_n = v_{n-1} - v_n$.

$$\frac{d}{dt}X = \frac{d}{dt}\begin{pmatrix} s_n \\ v_n \end{pmatrix} = \begin{pmatrix} \Delta v_n \\ a_n \end{pmatrix} \tag{1}$$

a_n denotes the acceleration achieved by vehicle n. The system is considered to be time invariant, i.e. the system dynamics model does not depend explicitly on time t. However, the achieved acceleration a_n is not exactly the desired acceleration u_n at same time t. This is due to the retarded execution of u_n owing to the actuator and vehicle dynamics in the closed loop system, as indicated in Fig. 1. The desired acceleration u_n is calculated by the upper level controller as the controlled input for the system. The formulation of the desired acceleration u_n is shown in (2).

$$u_n = \begin{cases} K_1 s_\Delta + K_2 \Delta v_n R(s_n), \text{ if } s_n \le r^{FRACC} \\ K_1 (v_0 - v_n) t_d, \text{ if } s_n > r^{FRACC} \end{cases} \tag{2}$$

K_1 and K_2 are the control gains, r^{FRACC} is the detection range of the forward looking sensor, s_Δ is the spacing error as shown in (3).

$$s_\Delta = \min\left\{ s_n - s_0 - v_n t_d, (v_0 - v_n) t_d \right\} \tag{3}$$

s_0 denotes the minimum space gap between vehicles at standstill, t_d is the desired time gap, and v_0 is the desired velocity in free flow mode. $R(s)$ is a space gap-dependent velocity-error response function for forward collision avoidance.

C. Collision Avoidance

As described earlier, collision avoidance schemes generally used in current FRACC systems have a drawback: the separate control strategy or the use of safety indicators within the desired acceleration formula lead to discontinuous accelerations [15] and therefore do not suffice for collision avoidance with smooth acceleration response.

The proposed FRACC uses an error response function $R(s)$, in the desired acceleration formula (2) for collision avoidance. $R(s)$ is formulated as a sigmoidal function of the forward space gap as follows:

$$R(s) = \frac{-1}{1 + Qe^{-\left(\frac{s}{P}\right)}} + 1 \tag{4}$$

where Q is the aggressiveness coefficient based on the maximum value of response, i.e. $R(s = 0)$. P is the perception range coefficient based on the detection range of the forward-looking sensors. Note that P is not the detection range. The sigmoidal formulation of $R(s)$ has various advantages compared to common safety indicator like inverse

time to collision $\frac{\Delta v}{s}$. Fig. 2 plots the graph of s^{-1} (the inverse time to collision indicator for a value of Δv=1) in blue and that of $R(s)$ in red. It can be seen that the response value of inverse time to collision rises suddenly at low spacing. This result in large jerk when the spacing is reduced suddenly (when a neighbor vehicle cuts in onto the same lane). Moreover as the space gap tends to zero, the response value of inverse time to collision theoretically tends to infinity, which is not technically feasible. These problems are eliminated in the $R(s)$ formulation. The proposed formulation invokes a strong braking response when approaching the preceding vehicle at small gap and a milder response when the preceding vehicle is further away. The use of $R(s)$ in Eq. (2) smoothly transitions the acceleration to zero over the sensor perception range. Fig. 2 also shows the variation in $R(s)$ with different P and Q, which indicates the possibility of parameterizing the controller to match the natural acceleration response of driver. In short, this approach facilitates effective response in critical situations and smoothens the transition towards non-critical vehicle states. The formulation of $R(s)$ with Q=1, P=100 (solid red line; Fig. 2) is used later in the performance analysis.

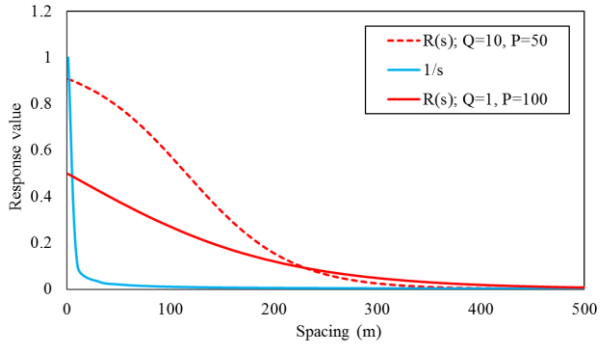

Figure 2. Comparison of different response functions for collision avoidance

D. Controller Constraints

The control law is subject to three constraints: allowable desired acceleration value is bounded in [-8, 1.5] m/s^2 interval under emergency braking situations based on the literature [14], [18]; the vehicle velocity is bounded between 0 m/s and maximum value v_{max}; spacing is restricted to positive values $s_n > 0$.

III. MATHEMATICAL ANALYSIS

The mathematical investigation detailed in this part is aimed at understanding the local and string stability properties of the FRACC controller and the theoretical capacity of the resulting flow. An ACC controller is locally stable if it can attenuate a disturbance to its velocity profile over time, and a homogenous vehicle platoon is said to be string stable if an initial disturbance decays upstream with the increase in vehicle indices in the platoon. This investigation omits the technical delay in the control loop due to lower level controllers and sensors. This is done to avoid the complexity in stability analysis of the delayed nonlinear controller. Therefore, the mathematical analysis will be performed assuming that the desired acceleration u_n is achieved instantaneously, making it the same as the achieved acceleration a_n (effects of feedback delay and lag will be addressed in section V).

A. Plausible Car Following Behavior

Here we check the plausibility of the controller as a car following model. Equation (5) shows that the desired acceleration of the ACC controller is a strictly decreasing function of the longitudinal vehicle velocity v_n and that the vehicle accelerates towards the desired velocity v_0 if not constrained by other vehicles.

$$\frac{\delta a_n}{\delta v_n} = -K_1 t_d - K_2 \left(\frac{-1}{1+Qe^{-\left(\frac{s}{P}\right)}} + 1 \right) < 0, \lim_{\substack{s\to\infty \\ v\to v_0}} a_n = 0 \quad (5)$$

Equation (6) shows that desired acceleration is also an increasing function of velocity of the predecessor.

$$\frac{\delta a_n}{\delta v_{n-1}} = K_2 \left(\frac{-1}{1+Qe^{-\left(\frac{s}{P}\right)}} + 1 \right) \geq 0 \quad (6)$$

Equations (5) and (6) hold for $Q \geq 0$; $P > 0$, and are consistent with plausibility criteria for car following models proposed in [19].

B. Stability Analysis

Here we analyse the local and string stability properties of the proposed FRACC system. Stability properties are studied by linearizing the system around an equilibrium state [20]. The equilibrium solution for identical vehicles using the proposed FRACC, can be derived with the condition $a_e = 0$ and $\Delta v_e = 0$. This equilibrium state is characterised by equilibrium velocity v_e as a function of equilibrium spacing s_e shown in (7).

$$v_e(s_e) = \begin{cases} \frac{s_e - s_0}{t_d} & ;if\ s_e \leq s_f \\ v_0 & ;if\ s_e > s_f \end{cases} \quad (7)$$

where, $s_f = v_0 t_d + s_0$ is the spacing threshold to distinguish cruising and following modes. Treiber et al. [19] show that any plausible car following model with $\frac{\delta a_n}{\delta v_n} < 0$ is locally stable. Equation (5) satisfies this criterion for positive values of K_1, K_2 and P and hence we conclude the controller to be locally stable.

Treiber et al. [19] introduced a linear stability analysis approach to investigate string stability of a vehicle platoon with ACC satisfying the criteria: $v_e(s_0) = 0$; $v_e{}'(s_e) \geq 0$; $v_e(\infty) = v_0$. These criteria are satisfied by the proposed controller as shown in (7), and therefore we use this approach for string stability analysis. For this, we consider the linearized equilibrium solutions for the closed-loop ACC system dynamics of an infinite homogenous vehicle platoon which is initially in equilibrium. We then introduce

perturbations in the form of linear modes with a real valued wave number k, and amplitude s and v as follows:.

$$s_n(t) = s_e + \hat{s}e^{\lambda t + ink} \text{ and } v_n(t) = v_e + \hat{v}e^{\lambda t + ink}, \quad (8)$$

where, i=$\sqrt{-1}$ is the unit imaginary number, s_e denotes the equilibrium spacing, k denotes the wavenumber and λ denotes the complex growth rate which has a real and imaginary part. Introducing the traffic wave ansatz into the microscopic traffic model based on the proposed controller, we understand that the growth rate $\lambda(k)$ and the wave number k has to be related by the characteristic equation (9).

$$\lambda^2 - \left(\frac{\delta a_n}{\delta v_n}\bigg|_e + e^{-ik} \frac{\delta a_n}{\delta v_{n-1}}\bigg|_e \right)\lambda + \left(1 - e^{-nk}\right)\frac{\delta a_n}{\delta s}\bigg|_e = 0 \quad (9)$$

where,

$$\frac{\delta a_n}{\delta v_n}\bigg|_e = -K_1 t_d - K_2 \left(\frac{-1}{1 + Qe^{-\frac{s_e}{P}}} + 1 \right) \quad (10)$$

$$\frac{\delta a_n}{\delta v_{n-1}}\bigg|_e = K_2 \left(\frac{-1}{1 + Qe^{-\frac{s_e}{P}}} + 1 \right) \quad (11)$$

$$\frac{\delta a_n}{\delta s}\bigg|_e = K_1 \quad (12)$$

String stability requires that perturbations introduced in the system are damped over time. This happens if and only if the real part of λ is negative in value for both the solutions of characteristic equation and for all possible wavenumbers, k. This leads to the string stability criterion (13).

$$v_e'(s_e) \le 0.5 \left(\frac{\delta a_n}{\delta v_{n-1}}\bigg|_e - \frac{\delta a_n}{\delta v_n}\bigg|_e \right) \quad (13)$$

By substituting (2) in (13), we get the stability criterion for the controller in (14).

$$\frac{1}{t_d} \le K_2 \left(\frac{-1}{1 + Qe^{-\left(\frac{s_e}{P}\right)}} + 1 \right) + 0.5 K_1 t_d \quad (14)$$

The parameter set meeting the criterion in (14) will ensure string stability of the proposed ACC platoon in the ideal case without system delay (see section IV for effects of delay and lag). Now, we calculate minimum threshold value of stable time gaps (t_d) for different values of equilibrium velocity v_e , using parameter values shown in Table 1.

The study compares the minimum threshold value of stable time gaps for proposed controller (P-FRACC) with a controller (MS-FRACC) with similar functionality, which was proposed by Moon et al. [14]. MS-FRACC has been selected as the benchmark as it was tested in a real vehicle and calibrated to match human behaviour. In this paper we have used the design parameter values suggested in the original paper. The results shown in Fig. 3 lead to the following insights into the properties of the proposed controller. Firstly, it shows that the minimum threshold value of stable time gap for the proposed ACC do not change significantly with increase in equilibrium velocity; on the contrary, the MS-FRACC is sensitive to the equilibrium velocity. This sensitivity is due to the formulation of feedback coefficients as a function of velocity. Secondly, it shows that the minimum threshold value of stable time gap of the proposed controller is sensitive to the aggressiveness coefficient Q. This means that by adjusting the value of Q, the proposed controller could achieve stability even at time gaps as low as 0.63 s; whereas for MS-FRACC, the minimum threshold values of stable time gap is as high as 1.41 s at equilibrium velocity of 90 km/hr. The ability of the proposed controller to maintain stability at low time gap is advantageous as lower gaps theoretically lead to higher capacity. In short, the study shows that the proposed control formulation under ideal conditions can be parameterized for a stable traffic flow with time gaps typically preferred by human drivers and even lower.

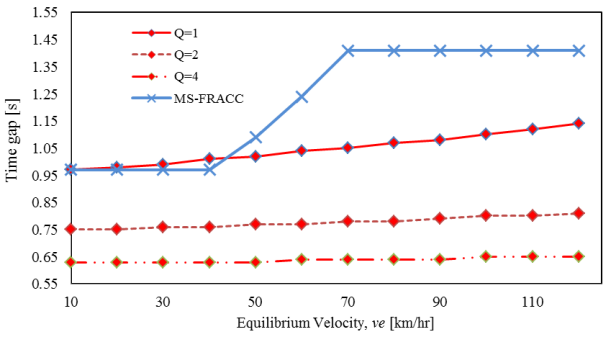

Figure 3. Minimum threshold time gap for string stability.

C. *Theoretical Roadway Capacity of Identical ACC Platoon*

Here we investigate the theoretical capacity of a homogenous vehicle platoon using the proposed controller (2). Using the concept of equilibrium state detailed in (7) and the relationship between local density ρ (number of vehicles in 1 km), space gap s (in m), and vehicle length l (in m) as $\frac{1000}{\rho} = s + l$, we model the fundamental diagram, which relates the steady-state traffic flow q (number of vehicle / h) with density ρ as $q = v_e \rho$. Assuming constant values for other parameters as shown in Table 1, we obtain a triangular fundamental diagram with a capacity of 2344 vehicles/hour/lane and critical density of 23 vehicle/km under a time gap setting of 1.2 s. Notice that these values are comparable to the capacity and critical density observed on highways [21].

IV. Experimental Design

In the mathematical analysis described in the previous section we used a simplified model omitting technical delay in the control loop. Therefore, in this section we describe the design of simulation experiments that allows performance evaluation of the controller under typical highway scenarios

with technical delay. The objectives of the experiments are: to check if the FRACC prototype satisfies the design specification; to verify the platoon performance of the controller. In these experiments, the controller is tested in comparison to a benchmark controller proposed by Moon et al. referred to as MS-FRACC [14].

A. Scenario Design

The performance of the FRACC vehicle is tested in different typical highway scenarios. These scenarios were previously used to test MS-FRACC [15], and are simulated with specific velocity profiles of an exogenous leader.

Normal scenario: it represents a typical highway scenario with velocity and spacing errors typically found under normal highway driving conditions. The velocity profile is shown in Fig. 7b

Stop and Go scenario: it represents a typical congested highway, when the vehicle might have to brake to a complete stop, and then accelerate back to track the velocity of the leader (See Fig. 4a). Here, the leading vehicle is initially at a constant velocity of 5.5 m/s, following which the leader vehicle begins to decelerate at time 5 s and thereafter comes to stop. The leader vehicle begins to accelerate at time 40 s to 15.6 m/s and then begins to decelerate at 130 s to reach a complete stop, which requires a braking of -0.39 m/s^2 for the next 40 s.

Emergency braking scenario: it represents a driving situation with a high risk of forward collision. Here, the leading vehicle brakes at time 60s from 22.2m/s to stop within 10s with deceleration of -4.45 m/s^2 (See Fig. 5b).

Cut in scenario: it represents a driving situation with sudden reduction in space gap, generally observed when a vehicle cut-in ahead on the same lane of the subject vehicle. Here, the leading vehicle is initially at a constant velocity of 22.2m/s and later the spacing between the leader and ego vehicle abruptly decrease by 50% at 60 s (See Fig. 6b).

Platoon driving: it represents the situation when a platoon of homogenous FRACC vehicles drives along the highway. The intention here is to analyze the platoon performance of the FRACC and test the mathematically identified stability properties. Towards this, we simulate two separate platoons of 11 vehicles under the normal highway scenario: The exogenous leader has a velocity profile as shown in Fig. 7a; the 10 remaining vehicles in one platoon use the MS-FRACC and the results are shown in Fig. 7a; remaining vehicles in the other platoon use the proposed FRACC and the results are shown in Fig. 7b

B. Controller Parameters

The feedback coefficients K_1 and K_2 were manually tuned to provide stable acceleration response for velocity and spacing errors under the typical highway scenarios described earlier. The initial values of these coefficients were set to 0. K_1 was found to be more sensitive than K_2, and therefore K_1 was changed incrementally by a resolution of 0.01, which reduced the oscillations; but after a certain value of K_1, maximum deceleration peak began to increase in cut-in scenario. Keeping this value of K_1, the value of K_2 was then incrementally changed by a resolution of 0.01 till the acceleration response in all scenarios ceased to overshoot and oscillate.

C. Technical Delay

We account for the sensing delay and non-linear longitudinal vehicle dynamics by incorporating a sensing delay and an actuator lag respectively in the simulation as detailed in [22]. The sensing delay τ_s is the delay with which state information is fed to the controller, meaning that the controller will use the state in a previous time instant as the input to calculate the desired acceleration at current time. The sensing delay is implemented as follows:

$$u_n(t) = K_1 s_\Delta(t-\tau_s) + K_2 \Delta v_n(t-\tau_s) R(s(t-\tau_s))$$
$$s_\Delta(t-\tau_s) = \min\left\{s_n(t-\tau_s) - s_0 - v_n(t-\tau_s)t_d, \left(v_0 - v_n(t-\tau_s)\right)t_d\right\} \quad (15)$$

The actuator lag τ_a implies the low pass filtered behavior of the vehicle in executing the desired acceleration signal given by the upper level controller. Actuator lag is implemented as follows:

$$\frac{da_n(t)}{dt} = \frac{u_n(t) - a_n(t)}{\tau_a} \quad (16)$$

Table 1 details the FRACC parameters values used in the study.

TABLE 1 PARAMETER AND COEFFICIENT VALUES

Notation	Parameter Details		
	Parameter/ coefficient	***Value***	***Unit***
l	Vehicle length	4	m
t_d	Desired time gap	1.2	s
s_0	Minimum space gap	3	m
v_0	Desired velocity	30	m/s
Q	Aggressiveness coefficient	1	-
P	Perception coefficient	100	m
K_1	Feedback coefficient-1	0.18	1/s^2
K_2	Feedback coefficient-2	1.93	1/s

D. Performance indicators

We simulate the temporal evolution of vehicle states using an update scheme with fixed time step of 0.1 s for 200 s. We use different indicators to interpret the simulation results. The rate of change of the achieved acceleration or jerk has been used by various researchers as an indicator of comfort and acceleration smoothness [23]. We use the Total Absolute Jerk (TAJ)-the absolute sum of the difference in achieved acceleration values between consecutive time steps for the entire simulation period-as the indicator of achieved acceleration smoothness, Maximum Absolute Jerk (MAJ) as the indicator of acceleration fluctuation, and Maximum absolute Relative Velocity (MRV) of the 1st and 10th follower in platoon as the indicator of error propagation.

V. SIMULATION RESULTS

The simulation results and their analysis are discussed in this section. Table 2 summarizes the values of indicators

obtained in simulation. We use typical values: τ_s = 0.2 s and τ_a = 0.2 s based on previous studies [22], [24], [25].

A. *Individual Performance*

To analyze the performance of an individual FRACC vehicle following a leading vehicle, we simulate the trajectories of one proposed FRACC vehicle and one benchmark MS-FRACC vehicle in different typical scenarios as described in experimental design. These scenarios are simulated by manipulating the acceleration profile of the exogenous lead vehicle, and the simulation results are described as follows:

1) Stop and Go scenario: the simulation results in Fig. 4 show that the proposed controller manages to track the preceding vehicle to a complete stop and subsequently accelerate (See Fig. 4b at 40 s).

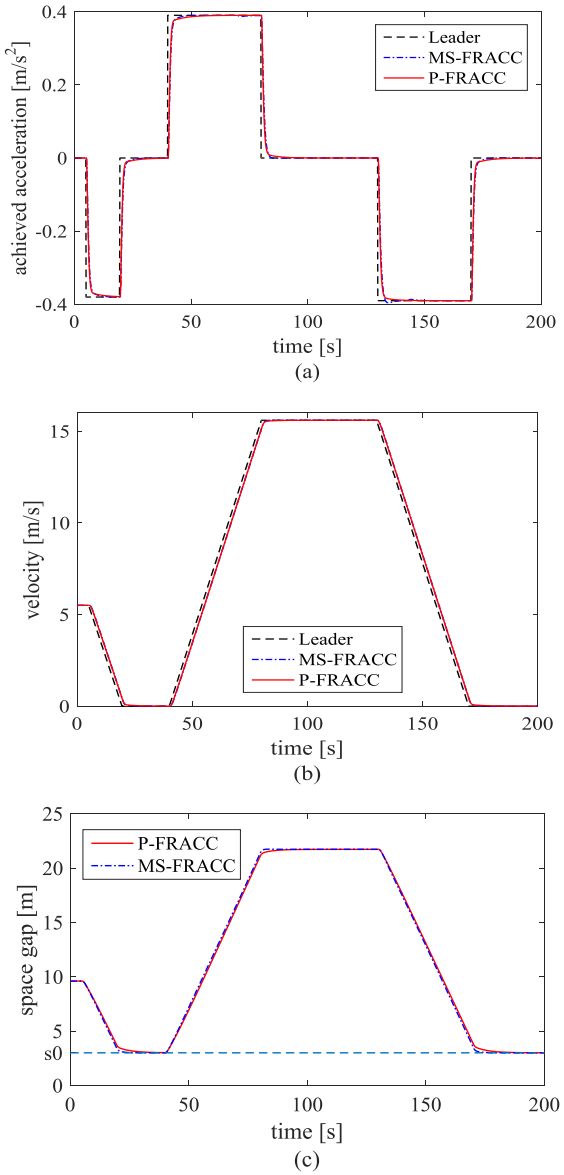

Figure 4. Performance analysis of P-FRACC and MS-FRACC in stop and go scenario.

The indicator values detailed in Table 2 show that the P-FRACC incurs smaller TAJ than MS-FRACC. The possible reason is that MS-FRACC has feedback coefficients as a function of velocity. Therefore, with varying velocity, this strategy leads to discontinuous desired accelerations. The analysis also shows that the proposed controller prevents the forward space gap from going below the safe minimum value s_0 throughout the simulation (See Fig. 4c).

2) Emergency braking scenario: The simulation results shown in Fig. 5 indicate that both controllers avoid a collision and maintain a safe minimum value s_0 throughout the simulation (See Fig. 5c).

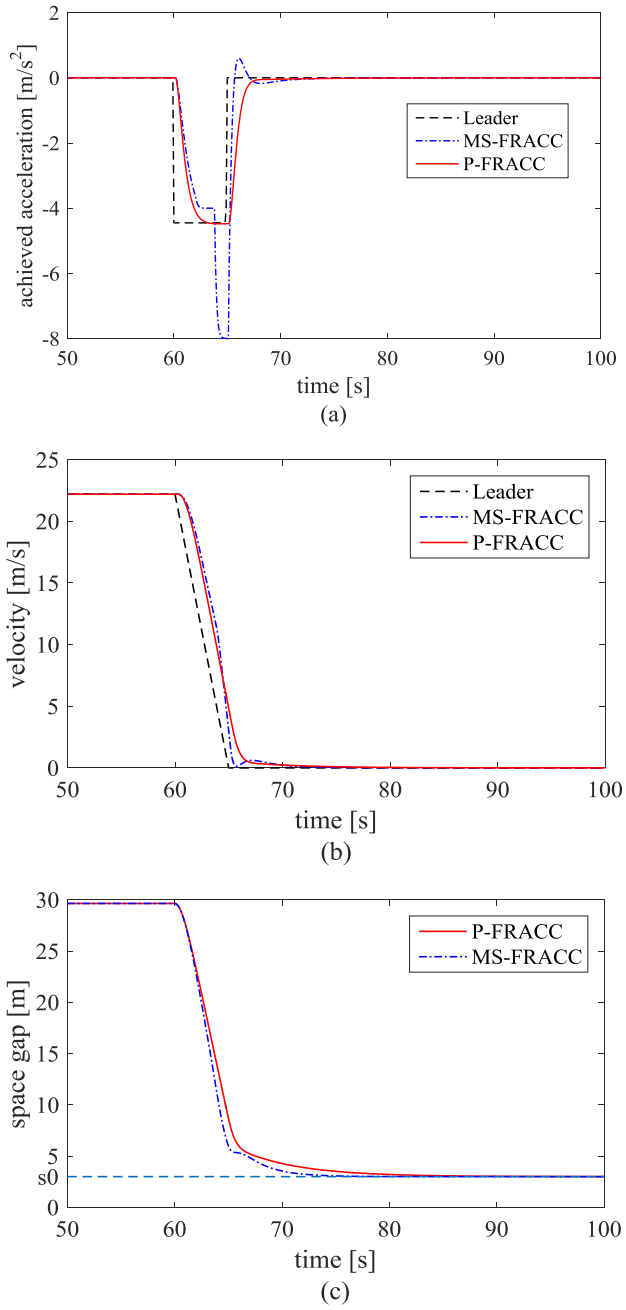

Figure 5. Performance analysis of P-FRACC and MS-FRACC in emergency braking scenario.

TABLE 2: INDICATOR VALUES OBTAINED.

Scenario	TAJ (m/s^3)		MAJ (m/s^3)	
	MS-FRACC	***P-FRACC***	***MS-FRACC***	***P-FRACC***
Stop &Go	2.34	2.31	0.03	0.03
Emergency braking	17.55	8.95	2.76	0.401
Cut- In	6.50	5.51	1.48	1.33

The indicator values in Table 2 show that the proposed controller leads to significant reduction in total, and the instantaneous jerk was maintained smaller than typical threshold value for comfort:1.5 m/s^3 [19]. On the contrary using the MS-FRACC, the instantaneous jerk was found to be as high as 2.76 m/s^3 (See Fig. 5a and Fig. 5b; 65s). Note that the collision avoidance schemes with separate control strategy (e.g. MS-FRACC) requires driving mode identification and controller switching, which may further retard the performance, when implemented in a real vehicle; the proposed controller uses a single control strategy and therefore could be faster.

3) Cut-in scenario: the simulation results in Fig. 6 show that both controllers lead to an acceleration fluctuation (See Fig. 6a) whereas the proposed controller leads to a lower drop in velocity (See Fig. 6b). Table 2 shows that the use of the proposed controller leads to lower values of TAJ and MAJ.

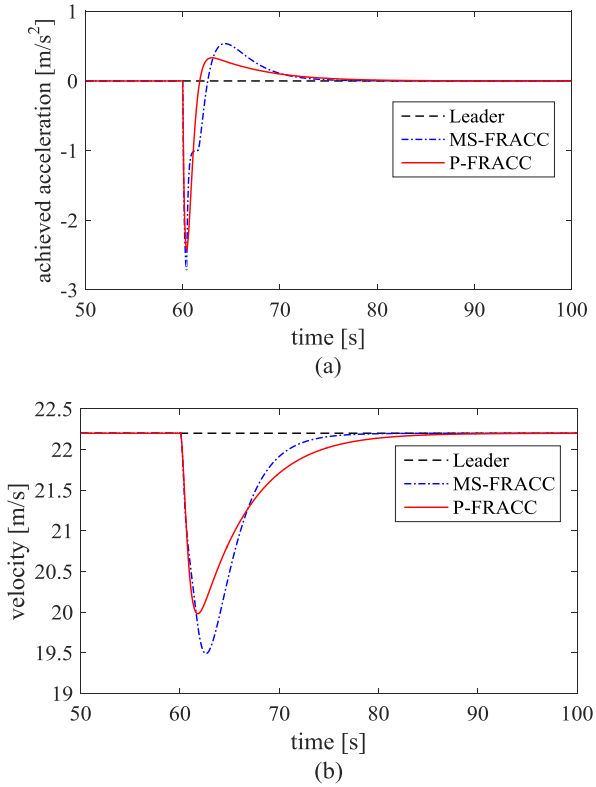

Figure 6. Performance analysis of P-FRACC and MS-FRACC in cut-in scenario.

B. *Platoon Performance*

The simulation results of the platoon driving scenario in Fig. 7c show that the use of the proposed controller diminishes the MRV from 0.59 (1st follower) m/s to 0.58 m/s (10th follower) i.e. the proposed controller attenuates the velocity error over the platoon with sufficient time.

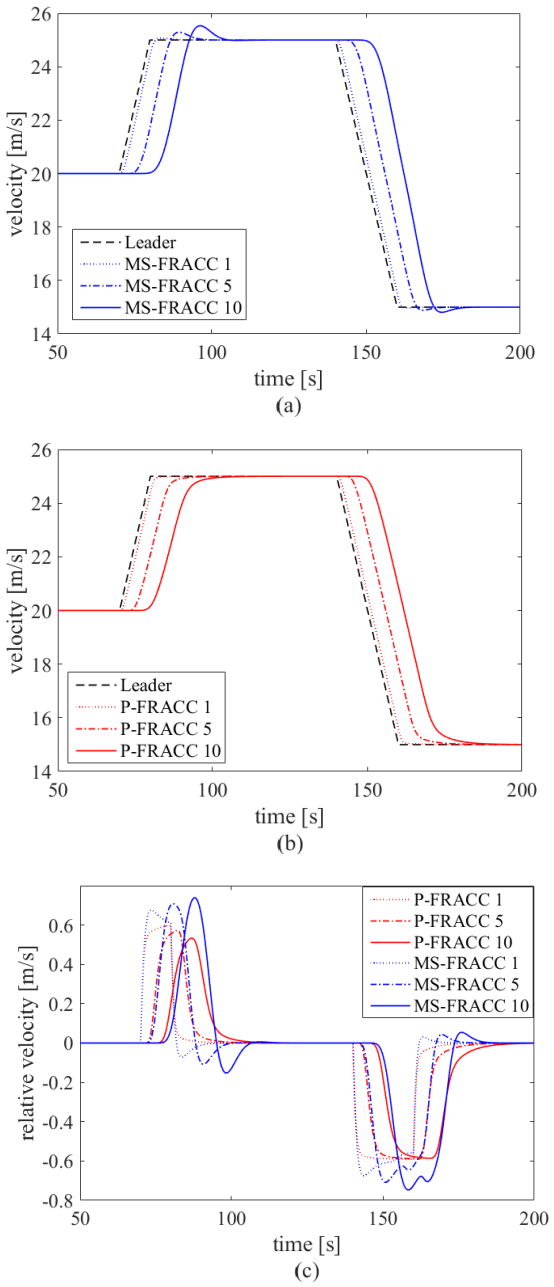

Figure 7. Platoon performance of a) MS-FRACC, b) Proposed-FRACC under normal scenario and c) Comparison of their relative velocity profiles.

On the contrary, the use of the benchmark controller leads to an overshoot in velocity (See Fig. 7a) and amplification in MRV from 0.675 m/s (1st follower) to 0.747 m/s (10th follower). The proposed controller also provides a smoother relative velocity profile under acceleration and braking (See Fig. 7c; 150s).

VI. CONCLUSION

In this paper we presented a Full Range ACC design with an integrated control strategy to smoothly handle vehicle control in critical highway scenarios, and examined its individual and platoon performance. This control strategy integrates adaptive cruise control and collision avoidance functionalities into a single mathematical formulation. The proposed controller displays a consistent performance in maintaining a forward spacing above the minimum value s_0 in all the critical highway scenarios used in this study. Simulation based performance analysis indicates that the proposed controller can effectively track the leading vehicle with a smooth acceleration response and significantly enhance comfort (reduce jerk) compared to a benchmark controller in emergency braking. Our results support the previous research findings [15] that using multiple control strategies leads to discontinuous accelerations. In line with the earlier research [23] we expect that the smoother acceleration profile by the proposed controller will lead comfortable highway cruising.

The proposed control strategy also displays an improved platoon performance compared to the benchmark controller. Both analytical results and simulation show the advantage of the proposed controller compared to the benchmark controller in view of string stability. The platoon simulation analysis accounting for the technical delay shows that the controller attenuates the velocity-error typical to a normal highway scenario under a time gap setting of 1.2 s. The performance assessment could be improved by using a vehicle model of higher fidelity and an optimisation based approach for parameter tuning. Furthermore, implementing the controller in real vehicles and testing with human subjects would aid parameter tuning for higher user acceptance. These topics will be taken up for future research.

ACKNOWLEDGMENT

This work is supported by STW Technology Foundation, the Netherlands, under the project "From Individual Automated Vehicles to Cooperative Traffic Management - Predicting the benefits of automated driving through on-road human behaviour assessment and traffic flow models (IAVTRM)"-STW#13712.

REFERENCES

[1] A. Vahidi and A. Eskandarian, "Research advances in intelligent collision avoidance and adaptive cruise control," *IEEE Trans. Intell. Transp. Syst.*, vol. 4, no. 3, pp. 143–153, 2003.

[2] G. Marsden, M. McDonald, and M. Brackstone, "Towards an understanding of adaptive cruise control," *Transp. Res. Part. C*, vol. 9, no. 1, pp. 33–51, 2001.

[3] D. Swaroop and J. K. Hedrick, "Constant Spacing Strategies for Platooning in Automated Highway Systems," *ASME J. Dyn. Syst. Meas. Control*, vol. 121, no. 3, pp. 462–470, 1999.

[4] M. M. Minderhoud, "Supported driving: impacts on motorway traffic flow," *Ph.D. dissertation*. Delft Univerisity of Technology, 1999.

[5] B. van Arem, C. J. G. van Driel, and R. Visser, "The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 429–436, 2006.

[6] S. E. Shladover, D. Su, and X.-Y. Lu, "Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow," *Transp. Res. Rec.*, vol. 2324, pp. 63–70, 2012.

[7] J. Zhou and H. Peng, "Range Policy of Adaptive Cruise Control Vehicles for Improved Flow Stability and String Stability," *IEEE Trans. Intell. Transp. Syst.*, vol. 6, no. 2, pp. 229–237, 2005.

[8] J. Wang and R. Rajamani, "Should adaptive cruise-control systems be designed to maintain a constant time gap between vehicles?," *IEEE Trans. Veh. Technol.*, vol. 53, no. 5, pp. 1480–1490, 2004.

[9] A. Kesting, M. Treiber, M. Schönhof, and D. Helbing, "Adaptive cruise control design for active congestion avoidance," *Transp. Res. Part C*, vol. 16, no. 6, pp. 668–683, 2008.

[10] J. Lygeros, D. N. Godbole, and S. Sastry, "Verified hybrid controllers for automated vehicles," *IEEE Trans. Automat. Contr.*, vol. 43, no. 4, pp. 522–539, 1998.

[11] R. Muller and G. Nocker, "Intelligent cruise control with fuzzy logic," in *Proceedings of the Intelligent Vehicles `92 Symposium.*, 1992, pp. 173–178.

[12] M. Wang, M. Treiber, W. Daamen, S. P. Hoogendoorn, and B. van Arem, "Modelling supported driving as an optimal control cycle: Framework and model characteristics," *Transp. Res. Part C*, vol. 36, pp. 574–563, 2013.

[13] M. Wang, W. Daamen, S. P. Hoogendoorn, and B. van Arem, "Rolling horizon control framework for driver assistance systems. Part II: Cooperative sensing and cooperative control," *Transp. Res. Part C*, vol. 40, pp. 290–311, 2014.

[14] S. Moon, I. Moon, and K. Yi, "Design, tuning, and evaluation of a full-range adaptive cruise control system with collision avoidance," *Control Eng. Pract.*, vol. 17, no. 4, pp. 442–455, 2009.

[15] D. Zhao, Z. Hu, Z. Xia, C. Alippi, Y. Zhu, and D. Wang, "Full-range adaptive cruise control based on supervised adaptive dynamic programming," *Neurocomputing*, vol. 125, pp. 57–67, 2014.

[16] A. E. Papacharalampous, M. Wang, V. L. Knoop, B. G. Ros, T. Takahashi, I. Sakata, B. van Arem, and S. P. Hoogendoorn, "Mitigating Congestion at Sags with Adaptive Cruise Control Systems," *2015 IEEE 18th Int. Conf. Intell. Transp. Syst.*, pp. 2451–2457, 2015.

[17] C. Nowakowski, S. E. Shladover, D. Cody, F. Bu, J. O'Connell, J. Spring, S. Dickey, and D. Nelson, "Cooperative Adaptive Cruise Control: Testing Drivers' Choices of Following Distances," California PATH Prog. Univ. of California, Berkeley, Res. Rep. UCB-ITS-PRR-2010-39, 2010.

[18] A. Kesting, M. Treiber, and D. Helbing, "Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity.," *Philos. Trans. A. Math. Phys. Eng. Sci.*, vol. 368, no. 1928, pp. 4585–4605, 2010.

[19] M. Treiber and A. Kesting, *Traffic Flow Dynamics: Data, Models and Simulation*. Heidelberg: Springer-Verlag, 2013.

[20] G. Orosz, R. E. Wilson, and G. Stepan, "Traffic jams: dynamics and control," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 368, no. 1928, pp. 4455–4479, 2010.

[21] M. Minderhoud, H. Botma, and P. Bovy, "Assessment of Roadway Capacity Estimation Methods," *Transp. Res. Rec.*, vol. 1572, no. 1. pp. 59–67, 1997.

[22] M. Wang, S. P. Hoogendoorn, W. Daamen, B. van Arem, B. Shyrokau, and R. Happee, "Delay-compensating strategy to enhance string stability of autonomous vehicle platoons," in *Transportation Research Board 95th Annual Meeting*, 2016, p. No. 16–2919.

[23] L. L. Hoberock, "A Survey of Longitudinal Acceleration Comfort Studies in Ground Transportation Vehicles," *J. Dyn. Syst. Meas. Control*, vol. 99, no. 2, p. 76, 1977.

[24] R. Rajamani, *Vehicle Dynamics and Control*, 2nd ed. New York: Springer Science & Business Media, 2011.

[25] G. Naus, J. Ploeg, M. J. G. van de Molengraft, and M. Steinbuch, "String-stable CACC design and experimental validation: A frequency-domain approach," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, 2010.