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Implementation and evaluation of cooperative adaptive cruise control functionalities

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Abstract: This study summarises the implementation of software system architecture and relevant modules to enable cooperative adaptive cruise control (CACC) functionalities as an extension of adaptive cruise control (ACC), thereby leveraging the lessons learned from prototype ACC vehicle testing as well as ideas from prior research. These activities were conducted in the United States under a cooperative agreement between the Crash Avoidance Metrics Partners, LLC and the Federal Highway Administration. A key outcome of this project was to understand the implementation of advanced capabilities for the CACC algorithm in a very structured manner. With the introduction of each CACC module, the impacts on the behaviours of vehicles following in a string (or string stability) were quantified to establish potential performance enhancements to automated following systems.

1 Introduction

The overriding purpose of this study is to describe the software implementation of system-level architecture and modules that enable cooperative adaptive cruise control (CACC) functionalities, drawing on results from an earlier study [1]. Subsequently, the string stability benefits of CACC relative to adaptive cruise control (ACC) are also presented. These activities were conducted as a part of the CACC small-Scale Test – Phase 1 project in the United States under a cooperative agreement between the Crash Avoidance Metrics Partners, LLC and the Federal Highway Administration (FHWA) [2].

Several software-based CACC modules are described in this study, including their functionalities and the reasons for creating them. These modules are used to simulate the CACC performance under the variation of different scenarios, road conditions, and vehicle types. The performance of these modules was characterised and optimised by on-road tests. The on-road tests used vehicles with different dynamic responses as a part of a single string. Four light-duty vehicles (hatchback, mid- and full-size sedans, large sports utility vehicle), each from a different automotive original equipment manufacturer, were retrofitted with common ACC and vehicular communication systems. Vehicles were tested under many different conditions to obtain performance data (e.g. radar sensor readings) when operating in a vehicle string. This data was then integrated into the simulation environment to develop and validate the CACC modules. A high-level block diagram of the CACC system architecture is seen in Fig. 1. There are seven CACC-specific blocks and they are depicted by blue-shaded boxes in the figure. *A key goal of the project was to investigate adaptation of longitudinal control systems to 'connected' or CACC.* For this reason, not only was an unmodified longitudinal controller was used, but the same automotive data and time-drive framework was used during the implementation of ACC and CACC [2].

Broadly, the capabilities of the CACC algorithm progressed from the (i) basic to (ii) multi-vehicle look-ahead (MVLA), and eventually to the (iii) merging assistant. The core CACC benefits can be realised with the basic implementation, including object fusion, target selection, and the longitudinal controller. The MVLA implementation extended increased string stability by utilising information from vehicles beyond the immediately preceding vehicle, and a real-time assessment of the communication quality to modulate the following gaps. The merging assistant augmented the MVLA to allow for a road-side infrastructure (e.g. a highway ramp meter) to aid merging.

1.1 Background and motivation

Table 1 is a consolidated view of the extensive literature survey that resulted in three broad categories to motivate the present work [3].

i. CACC for vehicle platooning.
ii. Human–machine interface (HMI)/driver vehicle interface (DVI) for vehicle platooning.
iii. Vehicle-to-vehicle (V2V) communication for the CACC application.

In Table 1, a significant majority (19 out of 26 papers reviewed in [3]) of the publications focused on some aspects of CACC platooning. The general concept of platooning and its various aspects (e.g. string stability, scalability, formation, and into the simulation environment to

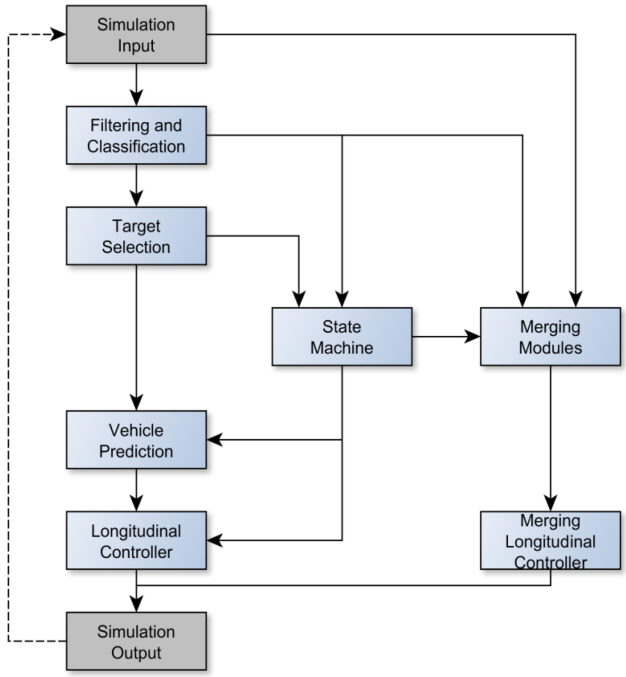

Fig. 1 *Block diagram of the CACC algorithm architecture*

Table 1 Extensive literature review helped to identify technical and safety issues, gaps in information, and challenges regarding the development of CACC systems. The concept of a string of vehicles as a platoon and associated issues in string stability and scalability were dominant themes of prior works. The publications and their numbering are shown in [3]

	Publication number																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
CACC for vehicle platooning																										
general concepts	í																í								í	
string stability and scalability			í		í		í								í				í	í			í			
formation, joining, leaving and size				í		í						í														
impact on traffic flow																					í	í		í		
SARTRE project									í	í	í															
HMI/DVI for platooning		í													í		í									í
V2V communication for CACC								í				í	í	í			í									
safety and/or reliability																										

management) have been investigated [4, 5]. These include the SAfe Road TRains for the Environment (SARTRE) project [6] and the FHWA-sponsored projects [7]. A few publications also addressed HMI and DVI issues for platooning operations (four out of 19 in [3]) and V2V communication for longitudinal control (five out of 19 in [3]). None of the publications addressed safety and/or reliability of a CACC. The outcome was a list of open technical issues that eventually motivated future research directions in order to fully develop the CACC application. The findings of the literature survey are listed below.

- Assessment of performance, safety, and reliability of CACC with V2V and vehicle to infrastructure (V2I) communication
- Reliability assessment of V2V messages for shortening the minimum headway achievable using ACC
- Assessment of communication latency and message loss
- Quantification of minimum transmission rates for messages between vehicles in a CACC string
- Understanding minimum performance requirements for a CACC system
- Understanding functional safety requirements

This paper is organised as follows. Sections 2 and 3 describe the software architecture for each module and state machine for the CACC implementation. Select time-critical performance enhancements to vehicle strings are described in Section 4, followed by the Summary.

2 Software implementation of the CACC algorithm

This section describes the components of each software block from Fig. 1.

2.1 Simulation input

Select simulation inputs are described below.

- Basic safety messages (BSM) (based on [8]) input receiver – to receive dedicated short range communication (DSRC)-based data elements from the other remote vehicles (RVs)
- Event input receiver – to receive event information from the simulation environment and forward it to other modules in the architecture. This includes manoeuvres triggered by the driver such as system activation/deactivation and modification of set speed and time-gap settings.
- Global positioning system (GPS) data receiver – to receive GPS coordinates from other RVs
- Radar data receiver – to receive host vehicle (HV) radar information and provide it to the other CACC modules

- Move data receiver – to receive vehicle sensor information from the simulation environment and provide it to the filtering and classification modules

2.2 Filtering and classification

This module filters and classifies the simulation inputs. The key blocks are itemised and described below, following the illustration in Fig. 2. The filtering and classification module receives and leverages BSM, GPS data, events, and other data inputs to determine communication quality, path prediction, object fusion and lane classification as explained below.

- Communication quality – is determined using information age (IA) and communication-induced tracking error (CITE) as the primary metrics

  IA is an indicator of the freshness of RV-based data and is expressed in milliseconds. IA depends on the data timestamps in the most recent BSM from a given RV and the current time. The lower the value of IA, the better the communication quality is with that RV.
  CITE is the two-dimensional distance between the current and estimated position of the RV, computed for each target RV. Lower values of CITE are preferred and are indicative of good communication channels with the RVs.
- Move data extractor – uses a simple vehicle-dynamics model to calculate the HV's movement in HV-centric coordinates and calculate displacements in *X*-axis, *Y*-axis, and yaw/heading relative to the previous timestamp when vehicle-dynamics data was received
- Micro rain radar (MRR) object validation – receives radar object information and verifies and improves object existence probability and movement state data
- Path prediction – calculates the predicted path of the HV based on its motion data. The data output is provided in the HV coordinate system
- Longitudinal classification – performs an initial filtering of objects identified from DSRC and the radar sensor and longitudinally categorises them based on the distance to the HV
- Object fusion – receives radar and BSM object information and fuses them when appropriate
- Lane classification – assigns objects into virtual lanes around the centre position of the HV based on their relative position. The result of the classification is appended to the information in the fused object list.

2.3 Target selection

This module receives the filtered and classified fused object data list and feeds the output to vehicle prediction, state machine, and the merging modules. This is illustrated in Fig. 3 and the key blocks are itemised and described below.

- Lane change detection – is responsible for calculating the probability that RV is performing a lane-change manoeuvre, either a 'cut-in' or a 'cut-out,' with respect to the lane of the HV. The current implementation considers relative yaw-rate, relative heading, lateral offset and turns signal activation.
- Primary target validation – selects a single primary target. Vehicles not perceived by the radar are filtered out to help with detection of RVs in adjacent lanes that are reported to GPS inaccuracies.
- In-lane assessment – aids longitudinal vehicle control based on data received from preceding vehicle(s) in the same lane, thereby verifying that the RV is driving in the same lane (as the HV)

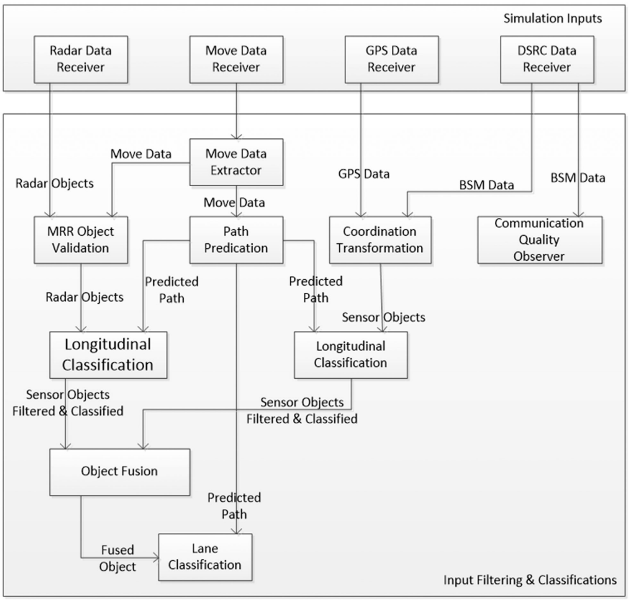

Fig. 2 *Filtering and classification module*

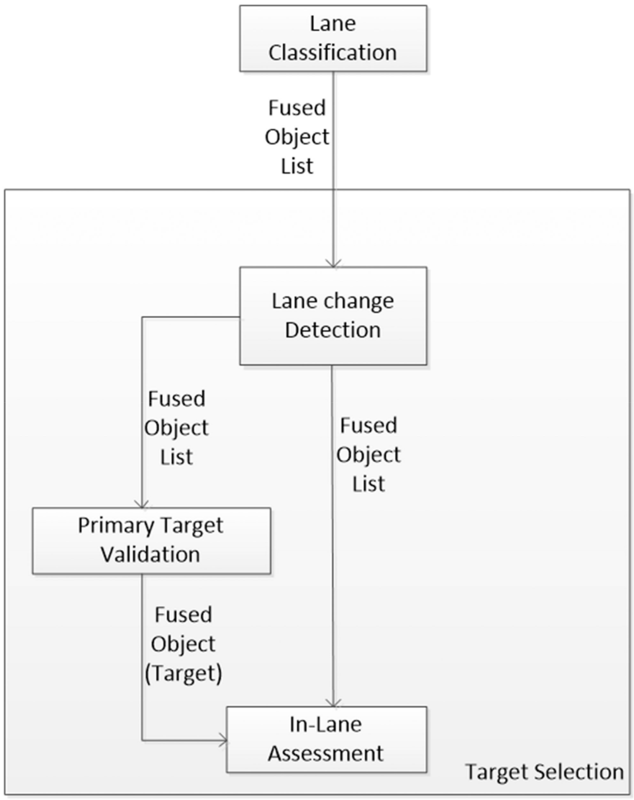

Fig. 3 *Target selection module*

2.4 Infrastructure assisted merge

CACC-equipped vehicles may encounter situations where merging traffic needs to be accommodated due to the small time gaps maintained by the vehicles. According to a CACC human factors study on merging behaviour [9], 18% of the merges in their study resulted in collisions. The high percentage of collisions in that study shows the importance of incorporating a method of merging into a highway containing CACC-equipped vehicles. A merge could be handled by the driver to manually incorporate merging traffic or could be implemented as part of the CACC functionality. Using CACC functionality in merging would be desirable since it would allow the driver to remain in a higher level of automation and, depending on the implementation, could lead to an improvement in the impact of merging manoeuvres on the surrounding traffic. The major blocks are described below and the illustration shown in Fig. 4.

- Infrastructure message assessment – is the gateway from the infrastructure messages to the vehicle, which receives and evaluates messages and determines the correct action
- Merging target modifier – modifies the lateral offset and longitudinal offset of the fused object (merging vehicle) based on the information from the infrastructure message and projects the fused object to the HV
- Merging flag switch – based on the current state of the merging flag, certain input variables from the time gap, state machine, and virtual target modules are passed through to the merging longitudinal controller.
- Merging target creation – after performing the projection of the sensor object onto the HV lane, creates a prediction of the position and speed of the sensor object and HV at the time of the merge and sets the virtual target for the HV
- Merging longitudinal controller – is a 1:1 copy of the main longitudinal controller but may operate prior to the merge and until the merge is complete

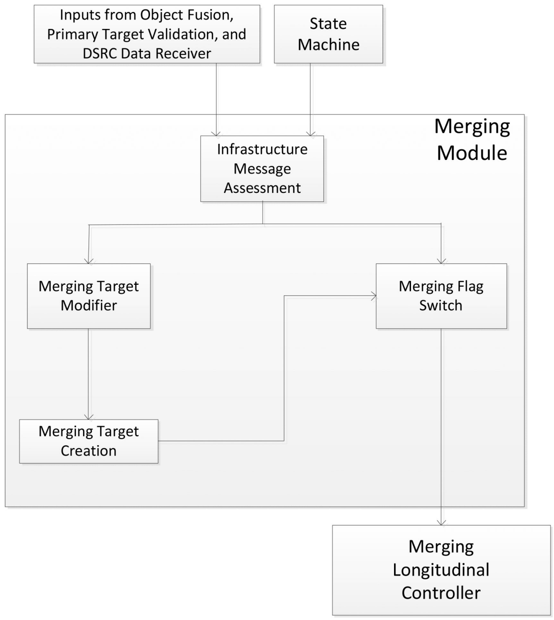

Fig. 4 *Merging module to ensure highway vehicles react to merging requests*

2.5 Vehicle prediction

The vehicle prediction module determines the require time-gap setting and create the virtual target. Fig. 5 provides an illustration of the vehicle prediction module with the descriptions of the main blocks below.

- Vehicle behaviour estimation – estimates the future behaviour of the preceding vehicles to be considered for setting time gaps
- First order lag look-up – models the acceleration command from the longitudinal controller based on the current vehicle dynamics conditions
- Virtual target creation – synthesises a virtual target based on on-board sensor measurements and, if applicable, V2V messages, and relays it to the longitudinal controller
- Time gap determination – identifies the appropriate time gap strategy for the current situation and operational state of the controller

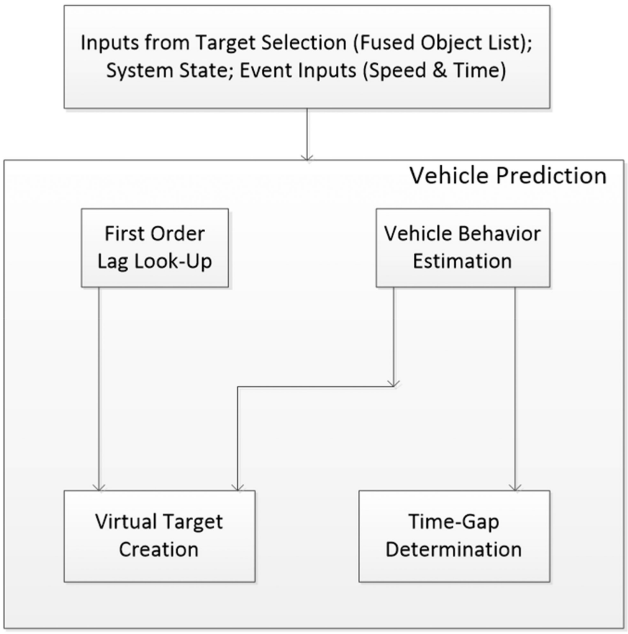

Fig. 5 *Vehicle prediction module*

3 State machine for CACC implementation

The state machine defines the high-level behaviour of the designed CACC system and its logical operating states. The CACC system has four main (or operating) states (manual, cruise control (CC), ACC, and CACC) and two temporary (or recovery) states (ACC recovery and manual recovery).

Each main state is associated with unique operational characteristics, and the conditions for transitions between the different states have been defined. They are described below.

- *Manual:* is the initial state when the CACC system is activated. The vehicle is fully controlled by the driver, while the CACC system monitors the surroundings through radar or DSRC.
- *CC:* The CACC system controls the vehicle's acceleration and deceleration by maintaining the internal set speed of the vehicle
- *ACC:* The CACC system controls the vehicle's acceleration and deceleration by maintaining a fixed time gap to the preceding vehicle based on radar data.
- *CACC:* The CACC system controls the vehicle's acceleration and deceleration by maintaining a time gap to the preceding vehicle as well as other control strategies such as MVLA or one-vehicle look-ahead (OVLA), which are considered sub-states of the CACC state. Whenever the system is transitioning into the CACC state, the OVLA sub-state is always entered first. The system automatical transitions from OVLA to the MVLA sub-state when one or more relevant vehicles ahead of the preceding vehicle are identified, or when the communication with the vehicle ahead is deemed reliable. Alternately, the system will transition automatically from the MVLA to the single-vehicle look-ahead sub-state when no vehicle ahead of the preceding vehicle can be defined through received BSMs, or when the communication with the vehicles ahead is deemed unreliable.

The recovery states exist to accommodate the transitions between the main states by allowing time for the operating conditions to stabilise. They are described below.

- *ACC recovery:* ensures the transition from the CACC to the ACC state is allowed only when the time gap, acceleration, and deceleration parameters are within the ACC's designed operating limits. This is done by potentially applying appropriate braking forces until all necessary conditions are satisfied for a safe transition to the ACC state.
- *Manual recovery:* provides safe transitions from the CACC state or the ACC recovery state to the manual state and ensures the driver's controllability of the vehicle. The manual recovery state applies appropriate braking force so the time gap is made large enough before transitioning to the manual state. The time the system spends in the manual recovery state depends on

	Manual	CC	ACC	CACC
Manual		Driver activation without target vehicle	Driver activation with target vehicle	No direct transition, only through CC and ACC
CC	One of the following conditions: a) Brake activation b) Driver system deactivation		Target acquisition	No direct transition, only through ACC
ACC	One of the following conditions: a) Brake activation b) Driver system deactivation c) Radar malfunction	Target loss		Reliable communication and localization
CACC	One of the following conditions: a) Brake activation b) Driver deactivation c) Radar malfunction (Through the Manual Recovery state)	Target loss	One of the following conditions: a) Unreliable communication b) Unreliable sensor fusion c) Unreliable localization (Through the ACC Recovery state)	

Fig. 6 *State transitions for CACC implementation*

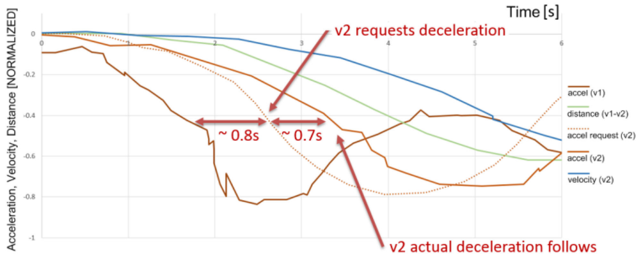

Fig. 7 *Temporal variations in normalised acceleration, velocity, and distance*

operating conditions preceding the transition to the manual recovery state. In the case of sensor faults leading to manual recovery, the time in manual recovery and associated deceleration values are determined with the help of the immediate last known valid sensor information.

Another feature in the CACC system is the manual override. The CACC system operates similarly to current production ACC systems from a driver's perspective, where the manual override feature is implemented in the CACC system. If the system is in the CACC state when the manual override is triggered, the system will fall back to ACC when the pedal is released. This ensures that a CACC re-acquisition of the communication is enforced. Fig. 6 illustrates the state machine for the designed CACC system.

4 Evaluations

4.1 ACC versus CACC

Two critical time intervals exist for vehicle string behaviour. First is the time to recognise a changing string dynamic and the second is the time to safely react to this change and reach a new steady-state. This behaviour is considered for each string member for the cases of ACC, CACC with OVLA, CACC with MVLA, and for predicted transitions. Beyond human reaction time, the vehicle systems induce a lag time due to the responsiveness of vehicle software and hardware. An example of this is shown in Fig. 7.

The experiments in this project were performed using a single-design ACC system added to all vehicles so as not to obscure the native vehicle response in the various models of vehicles. The native lag responses were thus preserved. In contrast, to base the work on a variety of ACC designs (those native to each vehicle) would obscure efforts to discover minimum performance requirements and to evaluate a string of multi-branded vehicles in a uniform fashion.

The formation of a vehicle string with various models of vehicle allowed an analysis of in-string responses, and the instantiation of the ACC characterisation baseline, in preparation

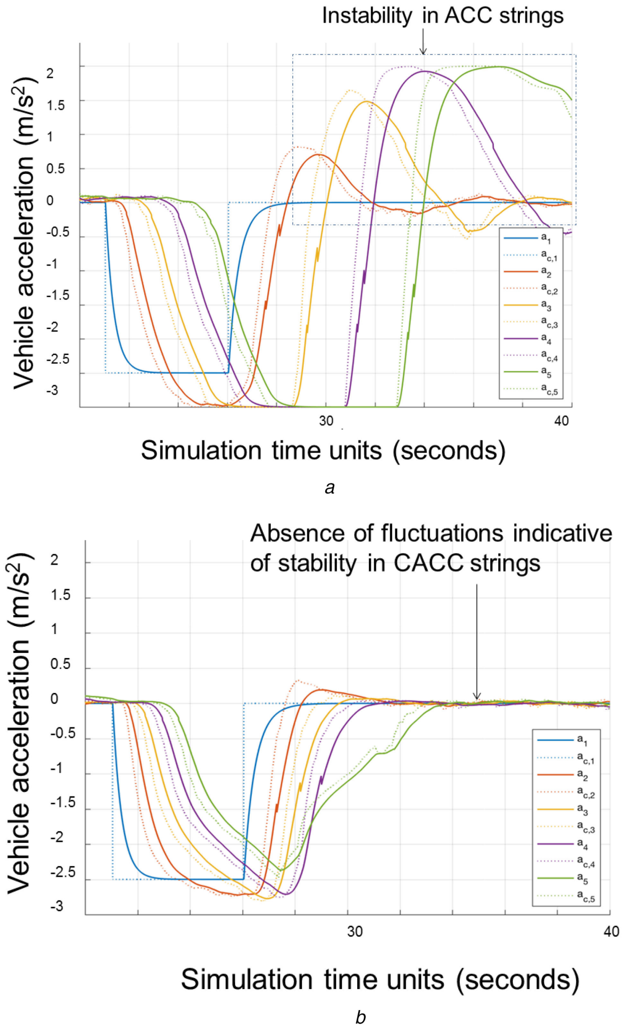

Fig. 8 *Acceleration profile of ACC versus CACC*

for the addition of a V2V communication link. This is shown in Fig. 8*a*. Once the 802.11p communication link was added, the benefits of this additional input could be evaluated. The result, shown in Fig. 8*b* was that V2V response was improved during the initial deceleration. One other significant response improvement occurred during the subsequent acceleration phase, where it was demonstrated that the oscillatory reactions were damped.

4.2 MVLA versus OVLA

In addition to software modules tuned specifically for operation in CACC mode, there are types of vehicle string management that offer specific safety gains. MVLA is one such mode and requires the exchange of vehicle IDs among all string members in such a way that the physical order in which vehicles are arranged in the string can be known and used to look ahead. This allows vehicles to know immediately the actions to be taken by the lead vehicle or any vehicle in the string, without passing information in series from V2V. In Fig. 9, the benefit of MVLA operation can be seen from the reduced oscillation near the end of the acceleration cycle, in comparison with OVLA.

Since the entire vehicle safety concept relates to the ability to avoid collisions, the comparison of OVLA to MVLA must be considered in terms of the resulting time gap. Fig. 10 shows that result, in which it can be seen the distance between string members in OVLA does decrease to a very small gap, while for MVLA the gaps increase uniformly, thus maintaining a more stable response.

5 Summary

This study presented the development of CACC-enabling modules to extend the capabilities of an ACC system. The different operational states and the transitions between them in the CACC

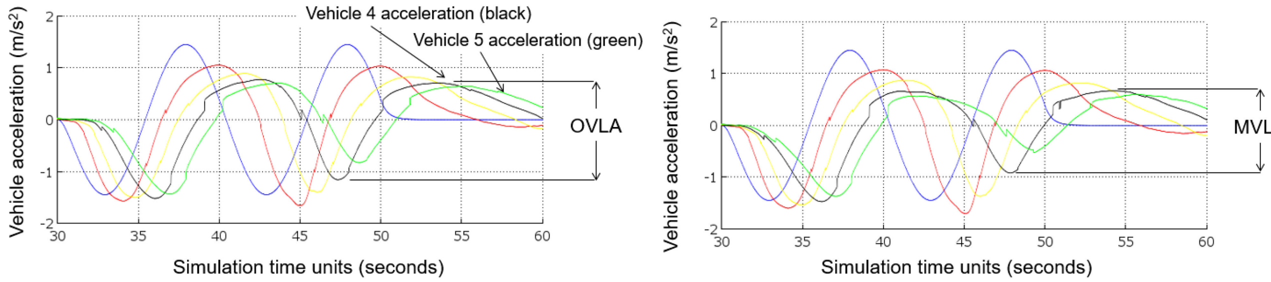

Fig. 9 *Comparison of acceleration for OVLA and MVLA*

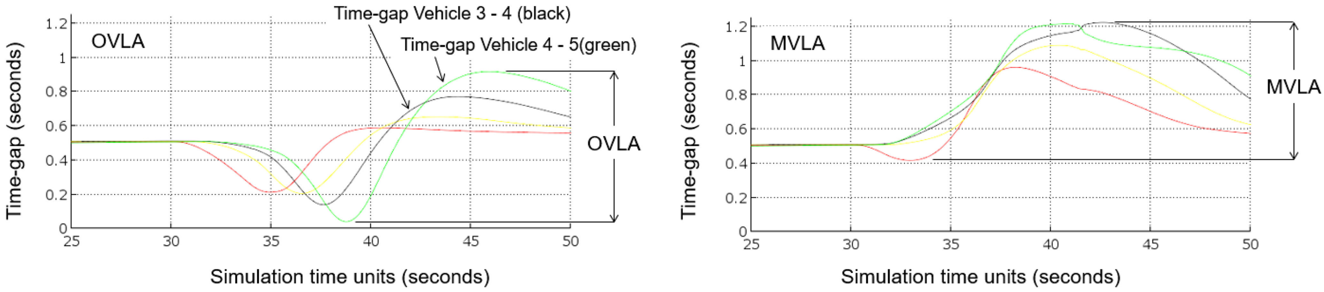

Fig. 10 *Comparison of time-gap for OVLA and MVLA*

implementation were described. By adopting a modular approach to adding CACC functionalities, it was easy to validate performance hypotheses and quantify potential performance enhancements for select automated following scenarios. The possible next steps would be to implement these CACC modules on the test vehicles and corroborate the simulation-based findings with on-road testing.

6 Acknowledgments

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