A Modular CACC System Integration and Design

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***Abstract*—This paper describes the Halmstad University entry in the Grand Cooperative Driving Challenge, which is a competition in vehicle platooning. Cooperative platooning has the potential to improve traffic flow by mitigating shock wave effects, which otherwise may occur in dense traffic. A longitudinal controller that uses information exchanged via wireless communication with other cooperative vehicles to achieve string-stable platooning is developed. The controller is integrated into a production vehicle, together with a positioning system, communication system, and human–machine interface (HMI). A highly modular system architecture enabled rapid development and testing of the various subsystems. In the competition, which took place in May 2011 on a closed-off highway in The Netherlands, the Halmstad University team finished second among nine competing teams.**

***Index Terms*—Cooperative adaptive cruise control (CACC), cooperative systems, Grand Cooperative Driving Challenge (GCDC), platooning, vehicle-to-vehicle communication (V2V).**

I. Introduction

COOPERATIVE adaptive cruise control (CACC) is one of many new proposed cooperative intelligent transportation system (ITS) applications enabled through wireless communication between vehicles. One of the main goals of CACC is to enable more efficient use of the existing road infrastructure, reducing road congestion and lowering fuel consumption.

CACC can be seen as an extension of already existing longitudinal control functions, with cruise control (CC) as a starting point. CC relieves the driver of maintaining a fixed speed; however, the driver must be ready to adjust the desired speed or brake if the preceding vehicle is slowing down. Adaptive CC (ACC) is an extension of CC, where onboard sensors, such as radar, are used to detect and measure the distance to the vehicle ahead. A vehicle that is put in ACC mode will automatically adjust its speed to the vehicle in front.

Due to delays in sensing the behavior of the preceding vehicle and actuating the own vehicle, amplifications in acceleration may occur, particularly if a constant spacing policy is used. If a third vehicle is following in ACC mode, it will experience an even stronger amplification of the acceleration. The longer the queue of vehicles, the stronger the required accelerations and decelerations will be, creating shock waves throughout the string of vehicles. The high required deceleration for vehicles in the back of the queue may, in extreme cases, leads to rear-ending accidents.

Fig. 1. Halmstad University competition vehicle: a Volvo S60 modified for CACC driving.

By introducing wireless communication between vehicles, a smarter CC can be achieved, and shock wave phenomena can be mitigated. In a CACC system, a vehicle does not solely rely on onboard sensors; instead, information is exchanged using radio communication between vehicles. A group of vehicles coordinating their speed using CACC is referred to as a *platoon*. By using radio communication, information about vehicles that are beyond line of sight (LOS) is made available, allowing members at the back of the platoon to adapt to vehicles further ahead, which has been shown to mitigate shock wave effects [1], [2]. In addition to lowered energy consumption due to smoother traffic, it has further been shown that reductions in fuel consumption due to reduced aerodynamic drag can also be achieved when vehicles are able to travel closer together in a platoon [3].

The Grand Cooperative Driving Challenge (GCDC) took place in The Netherlands in May 2011 and was the first competition of its kind. The purpose of the challenge was to bring together international teams, each implementing their own CACC system, to compete against each other in two scenarios, i.e., an urban and a highway scenario. Compared with earlier work on platooning, such as the Partners for Advanced Transportation Technology [4] and Safe Road Trains for the Environment (SARTRE) [5] projects, the competition aimed to highlight a largely unexplored aspect of cooperative systems: how can safe interaction between systems in a multivendor setting be achieved in practice?

This paper describes the CACC system and competition vehicle (see Fig. 1) developed by the Halmstad University team for the 2011 GCDC. The central challenges to participating in

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the competition and the main contributions of the paper are described. In Section II, a flexible and modular system architecture for rapid CACC development and testing is described. The architecture enables integration of both real-time automotive-grade systems and nonreal-time commodity systems for efficient prototyping in an academic setting. Section III details the implementation of the competition vehicle, including robust positioning, safety functions, and human–machine interface (HMI). In Section IV, a CACC controller based on the work by Naus *et al.* [6], [7] is described. Compared to the original definition, the modified control structure differs in the design of the feedforward filter to achieve string stability, as well as robustness against model uncertainties. The proposed controller structure also addresses discrepancies between preceding vehicle acceleration data received via radio and observations made with onboard sensors to increase system safety.

Test and competition results are presented in Section V. Finally, discussion and conclusions are given in Sections VI and VII, respectively.

A. GCDC Overview

The Netherlands Organization for Applied Scientific Research (TNO) initiated the GCDC [8] to "accelerate the development, integration, demonstration, and deployment of cooperative driving systems." The GCDC was designed as a competition open to academia and industry from across the globe with the intention to biannually hold the challenge after the inaugural 2011 competition in Helmond, The Netherlands. Scenarios for the 2011 GCDC required vehicles to exchange information and control their longitudinal acceleration to achieve stable and efficient traffic flow in two main scenarios.

The first scenario focused on the use of platooning in an urban setting to increase throughput at a cooperative signal-controlled intersection. Over several heats, the participating teams were randomly divided into two platoons and were challenged to minimize the time taken to cross the intersection for their own platoon. The teams were collectively evaluated on how efficient they were at passing the cooperative traffic lights in terms of the length of their platoon (expressed as the gap length to account for different vehicle sizes).

The second scenario showcased platooning in a highway setting. A GCDC lead vehicle, under the control of the organizers, drove as the first vehicle in the platoon and executed a predetermined speed profile to introduce acceleration disturbances (see Fig. 2). The teams in the platoon were individually judged on how well they could dampen out disturbances by incorporating information sent from other vehicles and how well they could maintain a speed-dependent reference platoon length. (For details on the evaluation criteria, see Section V-A.)

II. System Design

Halmstad University's participation in the 2011 edition of the GCDC was initiated in September 2010 as a project course for undergraduate students, in close collaboration with researchers and faculty at the university.

From an organizational perspective, the main challenges were related to the limited amount of time and funding available

Fig. 2. Competitors follow the GCDC lead vehicle in the highway scenario.

for the project. With the GCDC competition weekend scheduled for May 2011, the full development and testing cycle was limited to 9 mo.

From a technical perspective, the organizers' requirements on positioning accuracy and controller performance, coupled with the need for a flexible system architecture, were the central challenges.

In the succeeding sections, we first identify the constraints on the system design, and we then describe the main functions of the system and their interconnections. Finally, the mapping of functions to hardware is described.

A. Requirements and Constraints

Due to the time constraints of the project, the team decided that developing the physical actuators necessary for controlling a vehicle was infeasible and that the use of an already existing actuated vehicle platform was required. Furthermore, to enable easy testing of the developed system, it was early on decided that the road legality of the vehicle platform must be maintained. With regard to these two fundamental requirements, cooperation with an original equipment manufacturer (OEM) was deemed the most viable path, and a collaboration was initiated with the Volvo Car Corporation, which provided the team with a recent-generation Volvo S60 (see Fig. 1).

Maintaining compatibility with the OEM proprietary interfaces to the vehicle led to constraints being placed on software and hardware choices, as well as on the available sensor and actuator performance. Even with an OEM project partner, maintaining road legality limited the possible degrees of design freedom, and certain modules in the production vehicle such as engine control could not be modified without the need for

TABLE I
GCDC SENSOR AND CONTROLLER REQUIREMENTS

Value	Max	Min	Unit
Vehicle acceleration	2	-	m/s^2
Vehicle deceleration	4.5	-	m/s^2
Reported position error	1	-	m (2DRMS)
Reported velocity error	±0.5	-	m/s
Reported acceleration error	±0.2	-	m/s^2
Messaging frequency	10	10	Hz
Communication range	-	200	m

costly recertification procedures. Instead, longitudinal actuation was performed by providing a requested acceleration to the standard CC module in the vehicle. Since the communication format to the module is OEM proprietary and provided as precompiled Simulink blocks, this narrowed the scope of possible implementations.

The GCDC challenge organizers further defined several requirements on the quality of transmitted information, as well as on the acceleration performance of the participants, as summarized in Table I. The CC module in the Volvo S60 was able to meet the acceleration requirements without modification. The requirements on positioning accuracy were addressed by developing the high-accuracy positioning solution described in Section III-C.

The safety of the participants was also a highly prioritized requirement since, in contrast to challenges involving fully autonomous vehicles, the GCDC centered around cooperative driving with a human driver in the vehicle. The ability of the driver to override any automated function at any time was required.

To enable vehicles to exchange information, a mandatory wireless stack was defined by the organizers based on 5.9-GHz IEEE 802.11p [9]. Higher level standardized protocols included communications access for land mobiles (CALM)-FAST [10], on top of which a custom *GCDC interaction protocol* [11] was defined for platooning-related messages. The prescribed communication stack limited the choice of available hardware and software platforms able to host the communication functions. For example, the communication stack software provided by the organizers required the use of the Linux operating system.

B. Functional Architecture

Although only longitudinal control was required in the 2011 GCDC, a CACC system shares many properties with situated robot systems, such as the need to sense, interpret, and act in a physical environment. The Halmstad University system can, on a high level, be described by the three main tasks that it performs to perceive and act in a traffic scenario, i.e., *sensing*, *sensor fusion*, and *control* [see Fig. 3(a)].

During the sensing task, observations about the state of the environment are gathered. The state of the environment consists of basic physical properties (location, speed, heading, etc.) describing both the own vehicle and other vehicles. Furthermore, conceptual properties such as vehicle identity, vehicle role in the platoon (leader or follower), and infrastructure properties (traffic lights and speed limits) are also included in the state.

Three sources of state observations are used: 1) the *standard sensors* in the production vehicle (radar, lidar, camera, and own vehicle kinematics); 2) *additional sensors* added to the vehicle for the competition (Real-Time Kinematic Global Positing System (RTK-GPS) and inertial navigation system); and 3) *wireless communication* with other vehicles and infrastructure.

The sensor fusion task is responsible for mitigating inaccuracies in sensor data by combining data from several sensors. An example is the use of odometry data to improve positioning performance when Global Positioning System (GPS) coverage is poor or interpolation when radio messages from other vehicles are lost.

In the final control task, the improved state estimate is used to generate acceleration requests that are then actuated by the standard CC module in the vehicle.

The available sensors can be grouped into two classes: The first class contains the standard sensors, which are highly integrated in the vehicle and which adhere to strict timeliness guarantees. The second class contains the additional sensors, including wireless communication, where observations asynchronously arrive and with lower reliability. In the first class, failures may lead to catastrophic consequences (i.e., collisions), whereas, in the second class, failures are to be expected and should be accepted (e.g., lost radio messages or GPS signal loss). Similarly, the control task can be classified as a high-criticality task requiring guarantees on timely execution.

With these classifications in mind, a functional grouping has been performed to separate safety-critical functionality from nonsafety-critical functionality and to simplify mapping the functions to the available hardware architecture.

Two functional groups have been defined: the *inner loop* and the *outer loop* [see Fig. 3(b)]. The sensing task is performed in both the inner loop (using standard sensors) and the outer loop (using all three sources of state observations).

The task of issuing acceleration requests is performed in the inner loop based on either standard sensor data only or a combination of all three observation sources received from the outer loop. The inner loop is designed to function in ACC mode when no data are available from the outer loop (omission faults).

When detectable, faulty data from the outer loop (commission faults) are handled by assigning higher priority to in-vehicle sensors in case they differ from the extended state information. This could, for example, occur if the vehicle immediately in front reports a position that is inconsistent with the range reported by the onboard radar sensor.

III. SYSTEM IMPLEMENTATION

The vehicle used is a 2010 Volvo S60 (see Fig. 1) lent to the team by Volvo Car Corporation as the main competition vehicle. The vehicle is all-wheel drive and equipped with an automatic gearbox and a 205-hp diesel engine. It has a sensor package consisting of radar, lidar, and camera, which are used in the production vehicle to provide ACC, collision warning, and collision mitigation functions.

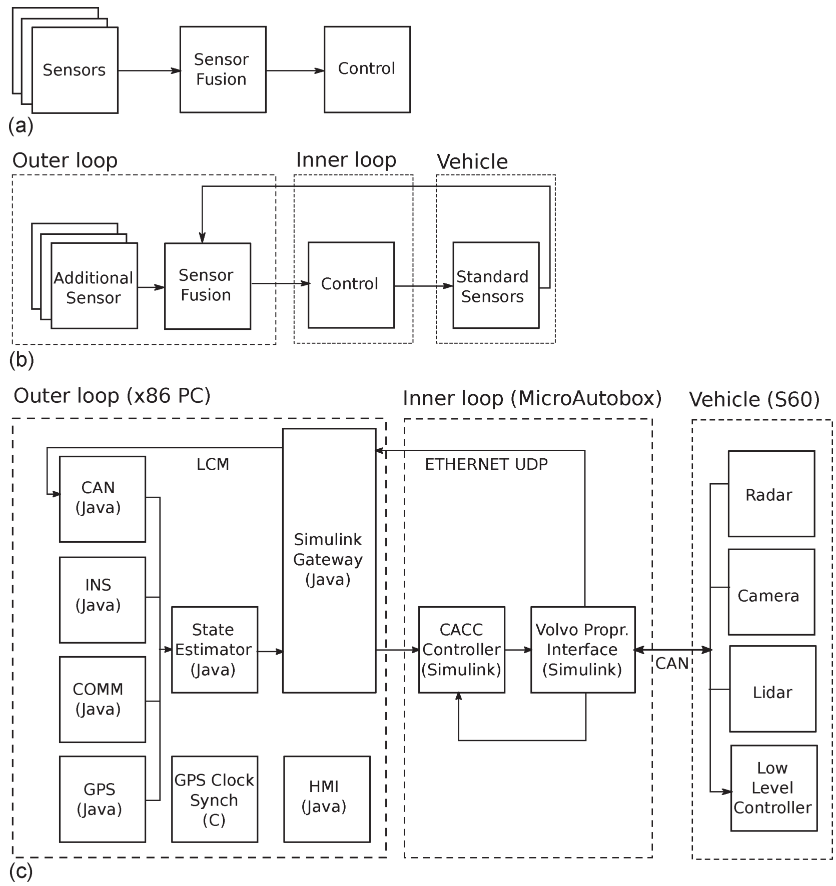

Fig. 3. Decomposition of system architecture from (a) basic system tasks to (b) functional groups to (c) functions mapped to hardware.

Two main computation units are used to host the two functional groups defined in the previous section [see Fig. 3(c)].

The outer loop functionality is implemented using an x86 PC of the type used in the European CVIS project [12] for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The unit is equipped with radio hardware that supports three different communication technologies, i.e., second-generation (2G)/third-generation (3G), IEEE 802.11a/b/g (WiFi), and IEEE 802.11p. The unit was selected since it was able to accommodate the necessary hardware and software drivers for 802.11p communication.

The inner loop functionality is implemented using a "dSpace MicroAutoBox" that enables MATLAB/Simulink code to be run with real-time guarantees. When connected, the MicroAutoBox interfaces with the CC module in the vehicle, enabling setting the desired acceleration (positive or negative) of the vehicle. Activation of the system and setting the maximum speed limit can be performed through the standard steering-wheel CC buttons. When driving on public roads, the MicroAutoBox is physically disconnected from the controller area network (CAN) buses, making the vehicle no different from a production vehicle and retaining its road legal status. The unit was selected because of its ability to guarantee real-time execution, as well as the fact that the Volvo proprietary interface was developed for this platform.

The x86 PC and MicroAutoBox units are connected to a wired Ethernet network using a standard WiFi-capable router. The MicroAutoBox is further connected to three of the vehicle's CAN buses, which enables it to both write and read from the buses. An "Apple iPad," which was used to display the HMI running in the x86 PC, is connected to the local network via 802.11g communications with the WiFi router.

The additional sensors consist of an RTK-GPS and an inertial sensor. The RTK-GPS is a "Trimble SPS-852" receiver connected via RS-232 serial cable to the x86 PC. The inertial sensor is an "XSens MTi-G," which is a full attitude and heading reference system that uses data from built-in accelerometers, gyros, magnetometers, barometer, and GPS. The MTi-G is connected via USB cable to the x86 PC.

The bulk of the hardware used is installed in the trunk of the vehicle (see Fig. 4), where a power distribution box controllable from the front seats provides 12 V from the vehicle power supply. A battery backup additionally provides power to selected systems when the 12-V supply is not available, such as when starting the vehicle. Mounted on the vehicle are antennas for RTK-GPS, RTK-GPS radio corrections, WiFi router, 802.11p communications, and reference GPS for the inertial system.

A. Interprocess Communication Framework

Modularization of functions into components with well-defined interfaces is a key feature in software design [13]. It allows functions to be developed and tested independently of each other, reducing system complexity.

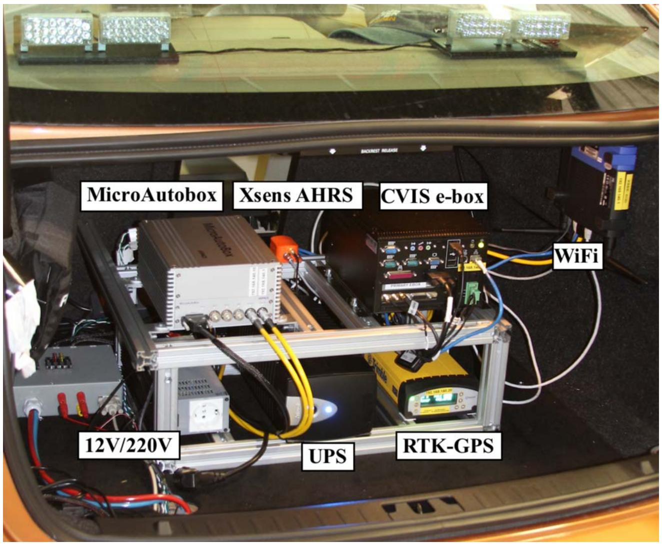

Fig. 4. Hardware installation in the trunk of the competition vehicle.

In addition, organizational complexities can be reduced, such as parallel function development, which was the case during the GCDC preparations, by defining module interfaces early.

To achieve a modular design, the interprocess communication framework lightweight communications and marshaling (LCM) [14] was selected early on in the project.

Developed to meet similar requirements by Massachusetts Institute of Technology for use in the DARPA Urban Challenge, LCM is an open-source framework for message passing and marshaling between processes implemented in a variety of programming languages (C, C++, Java, Python, MATLAB, and C#).

The framework does not rely on any centralized entity to broker communication between modules; rather, each module broadcasts messages to all other modules, which are then responsible for filtering out messages relevant to them.

The broadcast mechanism used is regular User Datagram Protocol (UDP) multicast, which allows for module interaction both on a single system and between multiple systems connected in any form of the Internet Protocol (IP) network. LCM is further lightweight by not requiring a separate process (or daemon) to handle communication; instead, the marshaling code is generated for a given target language and included together with general-purpose libraries in each module. An interface specification (referred to as a type specification in LCM) defines the format of messages and functions as a common ground for the various development teams.

Although MATLAB is listed as one supported language by LCM, the use of the generated marshaling code is implemented by linking to the generated Java code from MATLAB. This enables the integration of LCM modules with general MATLAB code; however, it is not an option in the case of code generated from Simulink/MATLAB for use on a real-time target, such as the MicroAutoBox. Thus, a Simulink gateway module was developed to handle communication between the inner and outer loop function groups using a proprietary message format over UDP.

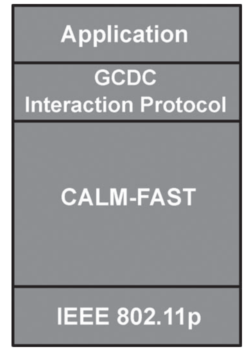

Fig. 5. GCDC communication stack.

B. Communication

The organizers of the GCDC defined the communication protocol stack required to take part in the competition (see Fig. 5). At the base of the stack, IEEE 802.11p [9] is found, which is an amendment to the ubiquitous wireless local area network standard IEEE 802.11. It specifies the physical (PHY) layer and the medium access control (MAC) layer. In the Halmstad vehicle, the MAC- and PHY-layer functionality is embedded in 802.11p chipsets from Atheros integrated in the x86 PC. Above the 802.11p, the CALM-FAST [10] protocol is found, which covers the network layer and the transport layer. It is developed with road traffic safety applications in mind, with a focus on minimizing protocol overhead and delay when traversing the protocol stack. On top of the CALM-FAST protocol, the specific GCDC interaction protocol [11] is found, which defines a common message set for the participating teams. The interaction protocol specifies 14 different messages that are used between vehicles and between vehicles and roadside units.

IEEE 802.11p is the selected technology for V2V communications at a carrier frequency of 5.9 GHz. It offers several different transfer rates, where a default rate of 6 Mb/s has been selected for communication in the GCDC competition. The output power used was 17 dBm (50 mW). A 10-MHz wide frequency channel is used, and vehicles transmit ten messages per second, containing the vehicle's position, time stamp, position accuracy, velocity, heading, acceleration, yaw rate, vehicle id, and platoon state. The position message is defined by the GDCD interaction protocol and has a total length of 32 bytes, excluding lower layer overhead.

C. Positioning

The GCDC competition rules dictated that vehicles must provide their absolute position with an accuracy below 1 m (2DRMS). In addition, the competition organizers provided a base station for RTK-GPS corrections, which led to the decision of using an RTK-GPS receiver to achieve the necessary absolute positioning accuracy.

RTK-GPS uses carrier phase calculations and corrections received via radio (400 MHz) from a fixed base station to calculate receiver position with centimeter accuracy. Although RTK-GPS typically provides high-accuracy position information, it also has drawbacks that must be addressed. When satellite visibility is low, such as when driving under a freeway overpass or close to tall obstacles, positioning accuracy is quickly degraded. Additionally, since the GPS provides only a point measurement, heading information is very poor at low speeds.

To counter these effects, RTK-GPS data are combined with wheel speed and steering wheel angle measurements from the CAN bus, together with data from an inertial sensor using an extended Kalman filter. The inertial sensor is used to provide reliable heading, velocity, and acceleration data. The filter uses CAN bus measurements in the prediction stage and RTK-GPS and inertial measurements in the update stage. (For an in-depth overview of a similar filter structure, see the work of Rezaei and Sengupta [15].)

State vector x consists of location (in a global metric coordinate system), velocity, and heading, i.e.,

$$x = [p_x \quad p_y \quad v \quad \phi]^T. \tag{1}$$

The nonlinear update stage uses CAN data to predict the state vector at time $t+1$, i.e.,

$$\hat{x}_{t+1} = \begin{bmatrix} p_{x,t} + \sin(\phi_t) v_{\mathrm{CAN}} \Delta t + \frac{\sin(\phi_t) a_{\mathrm{CAN}} \Delta t^2}{2} \\ p_{y,t} + \cos(\phi_t) v_{\mathrm{CAN}} \Delta t + \frac{\cos(\phi_t) a_{\mathrm{CAN}} \Delta t^2}{2} \\ v_{\mathrm{CAN}} + a_{\mathrm{CAN}} \Delta t \\ \phi_t + \dot{\phi}_{\mathrm{CAN}} \Delta t \end{bmatrix} \tag{2}$$

where $\dot{\phi}_{\mathrm{CAN}}$ is the yaw rate derived from CAN steering wheel angle measurements and a model describing the lateral dynamics of the competition vehicle, and a_{CAN} is the vehicle acceleration.

If measurement data are available from the RTK-GPS and inertial sensors, an update is also performed. If RTK-GPS or inertial sensor data are not available (such as when the GPS signal is lost), only the prediction stage is performed, leading to dead-reckoning solution until the GPS signal is recovered. To calculate the prediction covariance matrix, the Jacobian of the process model is evaluated around the predicted state at each time point and combined with estimated sensor noise.

D. HMI

To inform the driver and codriver about the state of the system, both during the competition and during development, a software-based HMI was developed. The HMI is executed on the x86 PC and allows the user to view status screens containing raw data for both standard and additional sensors, as well as a graphical representation of the location of nearby vehicles based on fused sensor data.

The user can also suspend and restart any individual module for testing purposes. To access the HMI, any WiFi-enabled device able to run a virtual network computing (VNC) client can be used. It is possible to connect multiple devices for a shared view of the HMI and to access the HMI from a remote location. Fig. 6 shows a dash-mounted iPad being used to access the HMI, together with screenshots for two of the subsystem views.

An additional engineering interface to the real-time MicroAutobox running the CACC algorithm was constructed in the dSpace ControlDesk environment, allowing controller

Fig. 6. HMI on a dash-mounted iPad, together with two example screens, showing the status of the inertial system and a representation of fused sensor data.

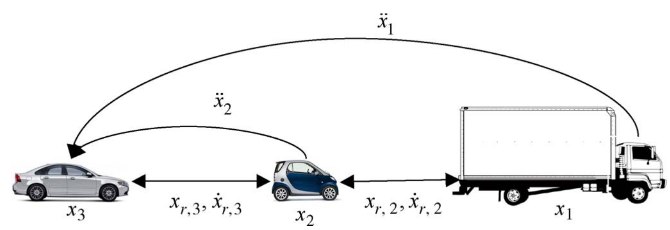

Fig. 7. Schematic of a platoon of vehicles equipped with CACC functionality.

parameters to be visualized and set from a laptop directly connected to the MicroAutoBox via Ethernet cable.

To meet GCDC safety requirements, an emergency button is integrated next to the driver's seat. In case of emergency, pushing the button will disable the power supply to the MicroAutoBox, thus disabling the custom CACC controller. There are also functions that disable the system when pressing the brake or gas pedals. Although not required by the GCDC organizers, safety measures have also been added during start-up, e.g., the system will only be activated when the driver's seat belt is fastened. A set of flashing lights has been installed on the front and the back of the vehicle to indicate the state of the controller. When the system has been disabled or deactivated, the lights will flash red. Otherwise, if the vehicle is in CACC mode, they flash green.

IV. Controller Design

A string of three heterogeneous vehicles is shown in Fig. 7. The primary objective is to make the ith vehicle follow the preceding $i-1$st vehicle at a desired distance $x_{\mathrm{rd},i}$ according to

$$x_{\mathrm{rd},i}(t) = r_i + h_i \dot{x}_i(t) \tag{3}$$

where r_i is the desired distance at standstill, h_i is the so-called *headway*, and $\dot{x}_i(t)$ is the velocity of vehicle i. The headway is the time that it takes for vehicle i to reach the current position of the preceding vehicle $i-1$ if it continues to drive with a constant velocity. It is shown in [6] and [7] that choosing

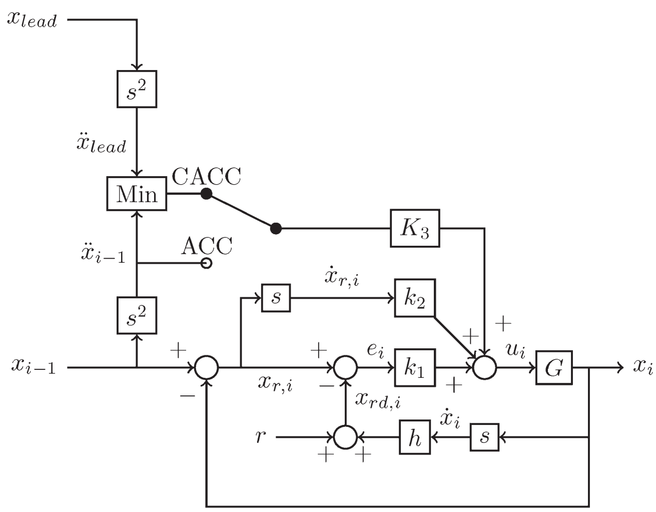

Fig. 8. Controller structure. When switching to CACC, feedforward control is based on the leading vehicle acceleration transmitted over radio.

a headway that is too small headway may lead to unstable behavior. For the GCDC competition, the minimum allowed headway was defined as $h = 0.6$ s. In the following, the control structure is focused on vehicle i, which is the ego vehicle, and subscript i is omitted from r and h for brevity. The relative distance between the preceding vehicle and the ego vehicle is

$$x_{r,i} = x_{i-1} - x_i. \tag{4}$$

This distance, which is referred to as *range*, is available from radar measurements as is its derivative, which is the range velocity. Within the production Volvo S60, there is a local control system for the acceleration, which can be described by the closed-loop transfer function parametrized with a time constant τ and a time delay τ_d as

$$s^2 G(s) = \frac{1}{\tau s + 1} e^{-\tau_d s}. \tag{5}$$

An index $G_i(s)$ may be used to indicate that each vehicle has its own dynamics but is omitted here. Thus, the position of vehicle i is $X_i(s) = G_i(s)U_i(s)$, with the control signal u_i being the setpoint acceleration for the local control system. The acceleration $\ddot{x}_i(t)$ is thus measured and used within the local control system. In addition, from the onboard sensors, the preceding vehicle acceleration can be estimated, $\ddot{x}_{i-1}(t)$. The vehicle therefore has available signals x_i, $x_{r,i}$, $\dot{x}_{r,i}$, $\ddot{x}_i$, and $\ddot{x}_{i-1}$ that can be used for ACC control. A simple control structure that directly uses these signals and that is easy to modify for CACC control is suggested. The structure is shown in Fig. 8. Compared with [6] and [7], the proposed control structure differs in several ways. First, rather than using a proportional–derivative controller in the inner loop as in [7], the derivative part is moved outside, based on $\dot{x}_{r,i}$ rather than e_i. This is for convenience since $\dot{x}_{r,i}$ is directly available. Second, the feedforward filter K_3 is not chosen to make $e_i = 0$ as in [7] but freely chosen in the design to achieve string stability. Filter K_3 is parametrized as

$$K_3(s) = \frac{k_3 + k_4 s}{1 + \tau_f s} \tag{6}$$

where k_3 is the proportional gain, k_4 is the derivative gain in the feedforward from the chosen acceleration signal, and τ_f is used to reduce the influence of noise. Third, the feedforward is based on the acceleration of a chosen leading vehicle and compared with the preceding vehicle acceleration, whereafter the minimum acceleration is chosen. The reason is to avoid overreacting on large accelerations, and also due to safety reasons, this strategy avoids the risk of coming too close to the preceding vehicle. In addition, the leading vehicle can be freely chosen, e.g., taking the one with most reliable radio connection. During the competition, the formal platoon leader was chosen as the leading vehicle. The communication delay has not been included in Fig. 8 for simplicity.

At the beginning of the urban scenario, the vehicles are standing still in front of either of the two traffic lights. In this starting configuration, the controller is disabled and is only activated once the closest traffic light in front of the vehicle transmits a message indicating that it has turned green.

The maximum speed of the vehicle was controlled by manually setting the speed limit of the standard ACC controller before each heat.

A. String Stability

String stability of a platoon means that oscillations from the leading vehicle should not be amplified downstream in the platoon. It is shown in [7] that an appropriate sensitivity function for heterogeneous traffic is

$$\mathcal{S}_i(s) = \frac{X_i}{X_{i-1}}, \qquad i = 2, \ldots, m \tag{7}$$

where m is the number of vehicles in the platoon. If X_1 is the leading vehicle, then $X_i = \mathcal{S}_i \mathcal{S}_{i-1} \ldots \mathcal{S}_2 X_1$, and a necessary condition to avoid amplification of oscillations is that

$$\|\mathcal{S}_i\|_\infty = \sup_\omega |\mathcal{S}_i(j\omega)| \leq 1 \qquad \forall i. \tag{8}$$

Consider the switch over to ACC in Fig. 8; then (with $r = 0$)

$$\mathcal{S}_i(s) = \frac{X_i}{X_{i-1}} = \frac{\left[k_1 + sk_2 + s^2 K_3(s)\right] G(s)}{1 + \left[k_1(1 + sh) + sk_2\right] G(s)}. \tag{9}$$

To achieve a string stable design, the interactive software *Sysquake* [16] is used. Function $|\mathcal{S}_i(j\omega)|$ is plotted against ω in a Bode amplitude diagram. Slide bars for controller parameters k_1, k_2, k_3, and k_4 are plotted in another figure. By changing the parameters from the slide bars, the Bode curve is instantaneously updated and is possible to get a feeling for how the different parameters influence the shape of the curve. The objective is then to adjust the parameters to achieve the entire Bode curve below gain 1.

B. Model Verification

Tests were performed to find the model describing the local closed-loop acceleration system in (5). The model time constant was found to vary, depending on speed, between $\tau = 0.4$ s and $\tau = 0.6$ s. Using Sysquake, a string stable design was developed, taking into account the variation of time constant

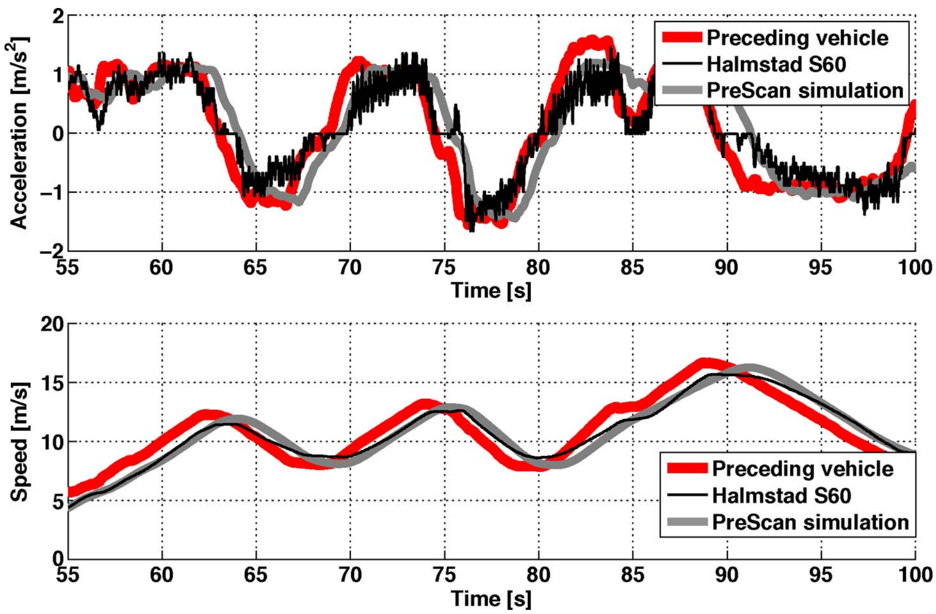

Fig. 9. ACC test with comparison between measured and modeled responses.

τ for robustness. An implementation of the controller, which was configured for ACC using the radar signal only, was then performed to fine tune parameters k_1, k_2, k_3, and k_4. In parallel, the model and the proposed controller were simulated in PreScan (which is a Simulink-based software for simulation and visualization of vehicle dynamics). A comparison between the simulated and measured responses is shown in Fig. 9.

The design was made for headway 0.6 s, which was achieved in practice. In addition, it was noted that the feedforward acceleration could tolerate a delay of 0.2 s although this had not been taken into account in the design.

C. CACC Testing

The development process used by the Halmstad University team is based on an iterative model, with regular releases of the system with gradually increasing functionality. During the fall of 2010, two iterations were made, with the first producing a benchtop system consisting of the basic services running against the PreScan simulator and the second producing an in-vehicle reference system running in a nonactuated Volvo S80. During spring 2011, a third iteration resulting in an actuated and cooperative Volvo S60 was performed.

To test the platooning behavior independent of other teams, a cooperative lead vehicle was developed. The lead vehicle (a Volvo S80) contains a CVIS communication and computation unit, which communicates as dictated by the GCDC interaction protocol. However, the lead test vehicle has reduced positioning capabilities, as compared with the competition vehicle, relying only on a consumer-grade GPS receiver. Additionally, it cannot be automatically controlled. The main reason for using a physical vehicle rather than simulating input to the competition vehicle is to verify exteroceptive sensors, such as radar and lidar. In parallel to the development of the physical systems, simulations were also performed using the PreScan simulator. PreScan provides an integrated environment for testing intelligent vehicle systems and vehicle sensors. Vehicles and control algorithms are modeled in MATLAB/Simulink, and simulations are then performed in a 3-D representation of the world, allowing realistic sensor outputs to be generated.

Together with the two other Swedish GCDC teams, a closed-track test of the CACC control approach was made, enabling testing with three vehicles involved. The resulting responses are shown in Fig. 10. During the test, the lead vehicle introduces acceleration disturbances while CACC is activated in the following vehicles with a headway $h = 0.6$ s. The Halmstad University vehicle is the last vehicle in the platoon. The results in Fig. 10 show how string stability is achieved by dampening of both the acceleration and velocity profiles of the lead vehicle.

One week before the challenge took place in May 2011, all teams were present in Helmond for precompetition testing. During the preparatory week, the teams had the opportunity to perform test drives on the competition highway, as well as on closed tracks in the area. A number of issues relating to differing interpretations of the communication specification were discovered and corrected during this time. Another problem that was discovered was that, since the GCDC lead vehicle drove between the two lanes on the highway, several of the teams had difficulties in correctly classifying it as a preceding vehicle using radar, due to limitations in the detection angle. The solution, as shown in Fig. 2, was to mount radar reflectors behind the lead vehicle on a frame extending into the adjacent lanes.

However, it was not until the final competition weekend that the teams had the chance to perform full-scale platooning with one another.

V. Results

During the competition weekend, the teams performed several successful platooning heats. For each heat, the platoon members were changed to evaluate team performance for various positions in the platoon.

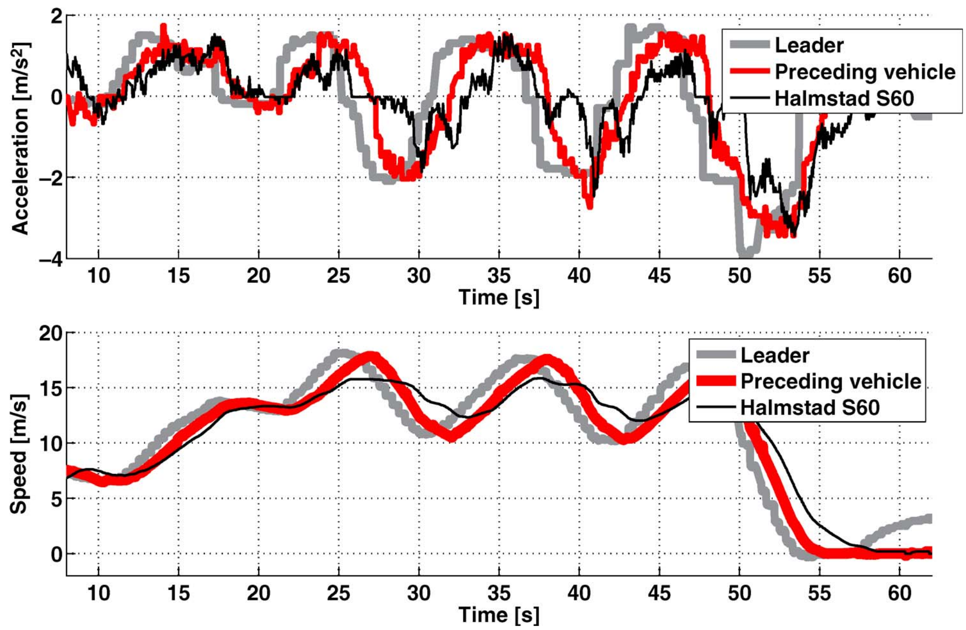

Fig. 10. CACC testing with three vehicles using cooperative information.

During the first day of competitions, the Halmstad University team participated in all platooning heats. In one of the heats, manual override of the system was required, due to the CACC controller braking heavily in response to incorrect position data sent from another team, falsely indicating that it had come to a complete stop.

At the end of the first day, a preliminary ranking indicated that the Chalmers team [17] was in first place with the Halmstad/Autopia/Futurum teams in shared second place and Scoop sharing third place with AnnieWAY [18]. Although several teams spent part of the night at the TNO facilities, it was decided by the Halmstad team that no modifications were to be made to the system after the first day of competition since the performance during the day had been satisfactory.

During the second day of competition, the Halmstad team successfully participated in all platooning heats without any mishaps. At the end of the competition weekend, it was announced that the Halmstad team had maintained its second place position but that team AnnieWAY had taken the first place and that team Chalmers had taken third place.

A. Controller Performance

During the GCDC competition, four evaluation criteria were defined to judge the CACC performance [19]. The criteria judge both the collective behavior of a platoon and the individual performance of the teams. The following four criteria were evaluated:

1) maximum throughput in the urban scenario;
2) maximum platoon gap length reached at the highway scenario;
3) platoon length variation during the highway scenario;
4) string stability.

String stability was evaluated for each vehicle only when being the second vehicle in the platoon (i.e., behind the GCDC lead vehicle).

The judges of the GCDC competition only reported a summarized score for all criteria weighted together. Therefore, individual criteria are not shown here. Our control design explicitly considers string stability, but the choice of headway also influences some of the other criteria.

For the first criterion, a fast control system is required. The second criterion judges the steady-state error of the whole platoon and is improved by choosing a smaller headway. A too small headway, however, may lead to oscillations, which are measured by the third and fourth criteria. Since each vehicle has its own communication structure, the feedforward acceleration can be different, depending on control structure. Therefore, the string stability criterion is only evaluated when the vehicle is placed just behind the lead vehicle.

Fig. 11 shows one of the heats during the competition where the Halmstad University vehicle was following directly behind the GCDC lead vehicle. The lead vehicle acceleration is clearly attenuated toward the end of the heat. Poor lead vehicle wireless data sometimes cause the nonideal behavior of the CACC controller, which is often correlated with passing under bridges on the competition highway (see time 460 s in Fig. 11).

B. Positioning Performance

During the challenge, the effects of GPS satellite outages were apparent, particularly under the bridges spanning the competition highway. Fig. 12 graphically illustrates the difficulties in maintaining a correct position in such circumstances for some of the teams.

Overreliance on the GPS in relation to other sensors is a likely cause of position errors that, based on Fig. 12, the teams chose to address in various ways. Vehicles B, C, and E continued transmitting updated position data, even under the bridge but with some bias, whereas vehicle D continuously transmitted the last known position until regaining GPS coverage after the bridge. Vehicle A appears to start dead-reckoning

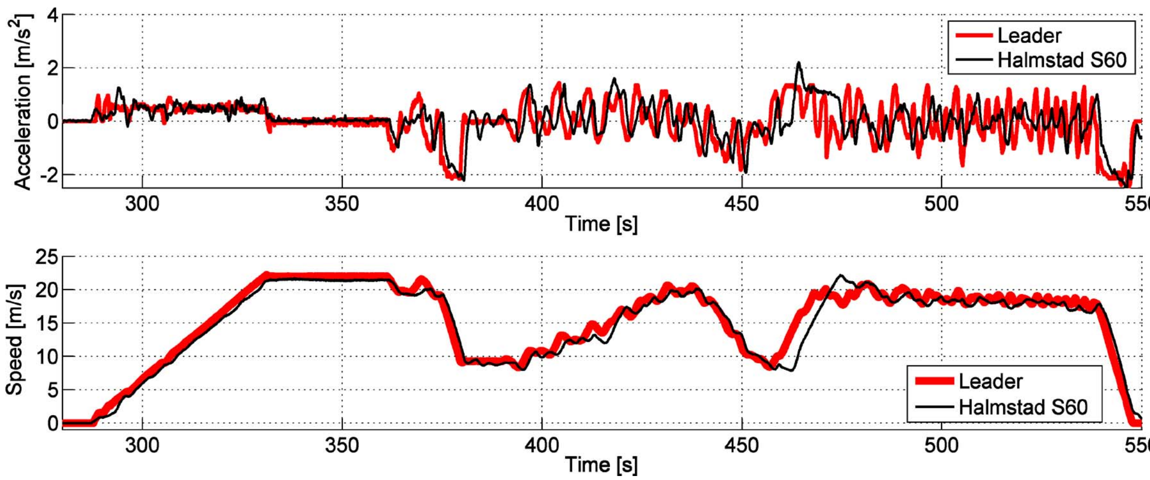

Fig. 11. CACC performance for one of the heats during the competition with the Halmstad University vehicle placed behind the GCDC lead vehicle. The lead vehicle passes under a bridge at time 460 s, resulting in degraded performance for the Halmstad vehicle due to errors in the position transmitted by the lead vehicle.

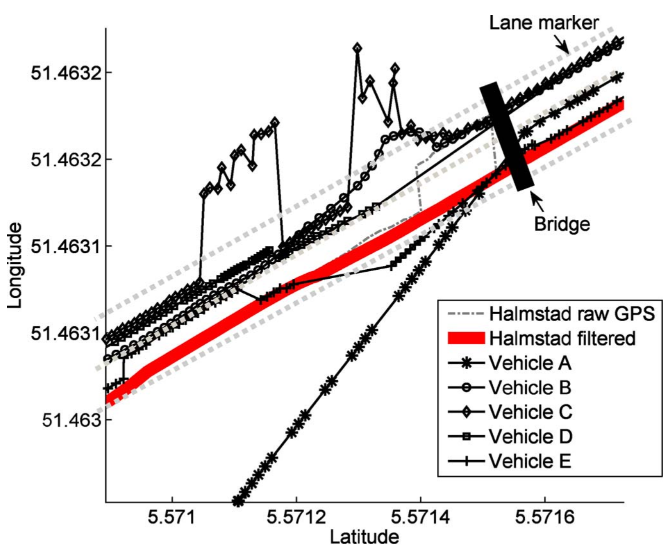

Fig. 12. Positioning performance of the Halmstad University vehicle in relation to a subset of the competitor vehicles when driving under a bridge. Position data for other vehicles are received via V2V communication. Direction of travel is from top right corner to bottom left corner. Several teams had difficulties under and after bridges when GPS coverage was lost. The Halmstad vehicle correctly filters out the GPS disturbance under and after the bridge.

after losing the GPS signal, possibly using erroneous heading information.

From a controller perspective, the behavior shown by vehicle D proved to be the most difficult to correctly handle as the transmission of a static position but with updated time stamps indicates that the vehicle has come to a complete stop. If the vehicle is immediately in front of the ego vehicle, this information can be marked as false by using onboard sensors; however, if the vehicle is further ahead in the platoon, this is not possible. The practical solution during the racing weekend was to employ manual blacklisting of some of the worst performing competitors based on the analysis of data taking place between heats. An interesting future improvement to the system is to automate this blacklisting process.

VI. Discussion

Although it is evident that the technologies and methods required to implement the individual components of a CACC system are mature already today, the integration of them into a reliably functioning system still poses a significant challenge. The Halmstad team's ability to address this challenge can, to a large extent, be attributed to choosing a highly flexible software architecture based on the LCM framework. This allowed decoupling of development teams, the use of a plurality of implementation languages, and frequent and early testing of individual subsystems.

There are also intersystem integration challenges. The interaction between CACC systems developed by a multitude of vendors, where information that originates within one vehicle affects the behavior in another, requires novel ways of ensuring the safe behavior of the system as a whole. Imprecise and erroneous location data were received from many of the other teams, particularly when traveling under bridges where RTK-GPS reception was poor. Since the proposed controller uses minimum acceleration of the preceding and lead vehicles, poor-quality wireless data caused unnecessary decelerations. This conservative control approach was chosen from a safety perspective; however, poorer performance than using pure ACC was observed when CACC input was erroneous.

Furthermore, to cooperate by wirelessly exchanging messages between vehicles requires communication standards. Currently, there are no communication protocols supporting the platooning application from a higher layer perspective in the protocol stack. In GCDC, the organizers developed their own message set to accommodate the platooning behavior, which is the GCDC interaction protocol. The SARTRE project [5] transmitted raw CAN data using UDP/IP to exchange platooning data [20]. The focus among the standard development organizations up until now has been on road traffic safety applications such as collision avoidance. However, standards are needed in a multivendor scenario to achieve the same platooning behavior. Wireless communication is inherently error prone due to signal fading, multipath, and path loss, which may destroy messages.

The high carrier frequency of 5.9 GHz selected for cooperative ITS is more limited in negotiating obstacles when compared with lower frequencies, and successful decoding of messages can drastically decrease when the LOS component is missing. This was specifically observed during the GCDC competition week when the LOS was blocked by the larger vehicles such as trucks. One countermeasure could be to relay data via intermediate vehicles to reach the destination or to find a lower carrier frequency for road traffic applications to extend the reliable communication range when the LOS component is missing.

An aspect that was not addressed in the 2011 GCDC is security. With communication standards and message specifications publicly disclosed months ahead of the competition, it would have been an easy task for a malicious attacker to sabotage the event. Spoofing the identities of other vehicles and sending messages from fake infrastructure, such as traffic lights, are examples of plausible attacks. Even with the addition of a security layer, denial-of-service attacks such as jamming of the 5.9-GHz or GPS channels would have highlighted further vulnerabilities of a cooperative platooning system.

VII. Conclusion

This paper has described the Halmstad University entry in the 2011 GCDC. A CACC controller, which is able to achieve string stable platooning, has been designed, implemented, and deployed in the competition, leading to a second place ranking out of nine competing teams. The control structure made it easy to switch between ACC and CACC, both of which were designed for string stability with robustness against variation in dynamics. The CACC design improved safety during decelerations.

An accurate positioning system based on fusion of RTK-GPS, inertial, and odometry data in an extended Kalman filter has further been presented and shown to be robust against GPS signal outages when passing under bridges during the competition.

The benefits of a modular system architecture have been shown by utilizing the LCM framework, which enabled a small team of undergraduate students to develop and test a functioning CACC system in less than a year.

The 2011 GCDC competition successfully showed cooperative platooning in a multivendor setting; however, several issues that should be addressed in future challenges were also identified, i.e., information security, non-LOS communication difficulties, and testing of the ability to comply with requirements on the quality of transmitted data.

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