Cooperative Adaptive Cruise Control Implementation of Team Mekar at the Grand Cooperative Driving Challenge

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***Abstract*—This paper presents the cooperative adaptive cruise control implementation of Team Mekar at the Grand Cooperative Driving Challenge (GCDC). The Team Mekar vehicle used a dSpace microautobox for access to the vehicle controller area network bus and for control of the autonomous throttle intervention and the electric-motor-operated brake pedal. The vehicle was equipped with real-time kinematic Global Positioning System (RTK GPS) and an IEEE 802.11p modem installed in an onboard computer for vehicle-to-vehicle (V2V) communication. The Team Mekar vehicle did not have an original-equipment-manufacturer-supplied adaptive cruise control (ACC). ACC/Cooperative adaptive cruise control (CACC) based on V2V-communicated GPS position/velocity and preceding vehicle acceleration feedforward were implemented in the Team Mekar vehicle. This paper presents experimental and simulation results of the Team Mekar CACC implementation, along with a discussion of the problems encountered during the GCDC cooperative mobility runs.**

***Index Terms*—Cooperative adaptive cruise control (CACC), cooperative systems, road vehicles, vehicle-to-vehicle (V2V) communication.**

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I. Introduction

COMMUNICATION units for cooperative mobility with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure) communication capability are expected to enter the market after the year 2015. The IEEE 802.11p Wireless Access in Vehicular Environment (WAVE) protocol will be the standard communication protocol for intelligent transportation system applications in Europe. This protocol is still under development, but software and hardware for its implementation became readily available in 2011. More detailed information on the IEEE 802.11p WAVE protocol can be found in [1] and [2]. There is considerable research effort on the development of V2V communication units, roadside units (RSUs), and applications that use these units (see [3], for example). Cooperative adaptive cruise control (CACC), which is an extension of adaptive cruise control (ACC), is one of these applications.

ACC systems have been available on the market for some time. Milanes *et al.* [4] have experimented with three communicating autonomous vehicles in close environments. Their experiments concentrated on ACC and intersection maneuvers among the cars, as well as emergency stops. String stability is an important criterion for ACC systems and has been the topic of many studies. Xiao and Gao [5], for example, have investigated the practical string stability of platoons of adaptive cruise control vehicles that apply the constant time headway spacing by considering the parasitic time delays and lags of the actuators and sensors when building the vehicle longitudinal dynamics model. Moona *et al.* [6] report work on an ACC system design with integrated collision avoidance.

The aim in ACC is to reduce headway time as much as possible, without violating string stability. CACC extends the capability of standard ACC by communicating information about the state of the preceding vehicle, thereby reducing the headway time used in standard ACC. In case of loss of communication, CACC keeps operating as an ACC system. The use of smaller headway time is expected to have a positive influence on traffic flow rate [7]. CACC is also expected to outperform ACC in damping traffic shockwaves [8]. Oncu *et al.* [9] approached the design of a CACC system from a networked control system point of view and investigated how string stability is affected by network-induced effects such as delays. The motivation of the GCDC was to use smaller headway times to improve traffic flow rate and to damp out shockwaves in traffic through the use of CACC.

ACC and CACC systems have higher and lower control levels. The higher level is a supervisory controller that switches between the states of automated driving. The low-level controller is essentially a throttle/brake controller that regulates the desired headway time. Different low-level ACC/CACC controllers have been used in the literature. The ACC system in [6] was based on sliding-mode control. The low-level feedback controller that was used by Ploeg *et al.* [7] was proportional–derivative (PD) second-derivative control. Oncu *et al.* [9] used a PD-type ACC/CACC feedback controller. Desjardins and Chaib-draa [10] used reinforcement learning for their CACC control.

This paper presents the CACC implementation of Team Mekar in the Grand Cooperative Driving Challenge (GCDC), which was organized by TNO and High Tech Automotive Systems (HTAS) in The Netherlands as a cooperative mobility demo of the CACC technology on the A270 Highway between the cities of Helmond and Eindhoven (see [11] for details). The Team Mekar vehicle is shown in one of the GCDC heats right after the TNO lead vehicle in Fig. 1. The IEEE 802.11p WAVE communication protocol was used by all the participating teams. The challenge included both a traffic light and an urban driving scenario. The low-level ACC/CACC feedback controller that was used by Team Mekar is a PD controller similar to the controllers in [7] and [12]. The CACC method that is used is not unique and is based on the CACC implementation in [12]. The main goal and contribution of this paper is to present the scientific lessons that were learned and the experimental results that were obtained by Team Mekar in the GCDC challenge, because they illustrate potential problems that may take place in cooperative mobility experiments. This paper and the experimental results also show that communicated–Global Positioning System (GPS) information can be used to implement ACC and CACC. Although it is currently an expensive solution, this approach may be feasible in the future if high-update-rate GPS/inertial measurement units (IMUs) of reasonably low cost become readily available.

The rest of this paper is organized as follows. Section II gives a brief overview of the Team Mekar GCDC vehicle platform, which is composed of its autonomous throttle and brake actuation, the sensors used, and the communication system. The longitudinal vehicle dynamics model that was used is presented in Section III. The CACC implementation that was used is given in Section IV, along with an analysis of some experimental data from the GCDC heats. A speed profile following the experiment conducted after the GCDC is also presented and analyzed in Section IV. This paper ends with conclusions and recommendations in the last section.

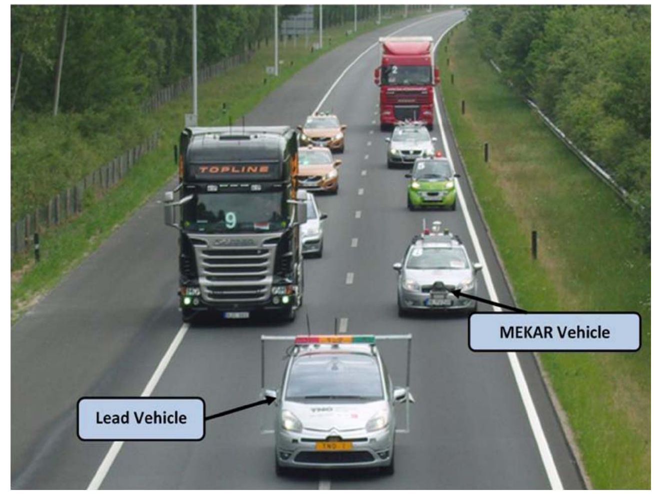

Fig. 1. Team Mekar vehicle (number 8) in a GCDC heat.

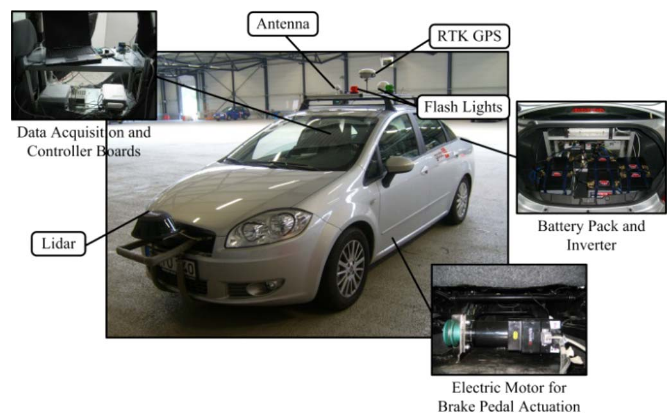

Fig. 2. Team Mekar GCDC 2011 vehicle sensors, actuator, and control units.

II. Brief Overview of the Team Mekar Vehicle Platform

The Team Mekar vehicle is a midsize sedan that is powered by a 1.3-L 90-hp multijet diesel engine and is equipped with an electronic stability program and cruise control. It has a dualogic automatic transmission. The Team Mekar GCDC vehicle is shown in Fig. 2 inside the Vehil Laboratory during the preparation week of GCDC. The sensors, actuators, control units, and electrical system of the Team Mekar vehicle are illustrated in Fig. 2. The flow of information between the sensors, actuators, and control units is illustrated in Fig. 3. The low-level control and CACC algorithms reside in a dSpace microautobox, which is programmed in the Simulink environment. The gas pedal signal is directly read by the low-level controller in the dSpace microautobox and modified according to the CACC algorithm. An electric motor with a controller area network (CAN)

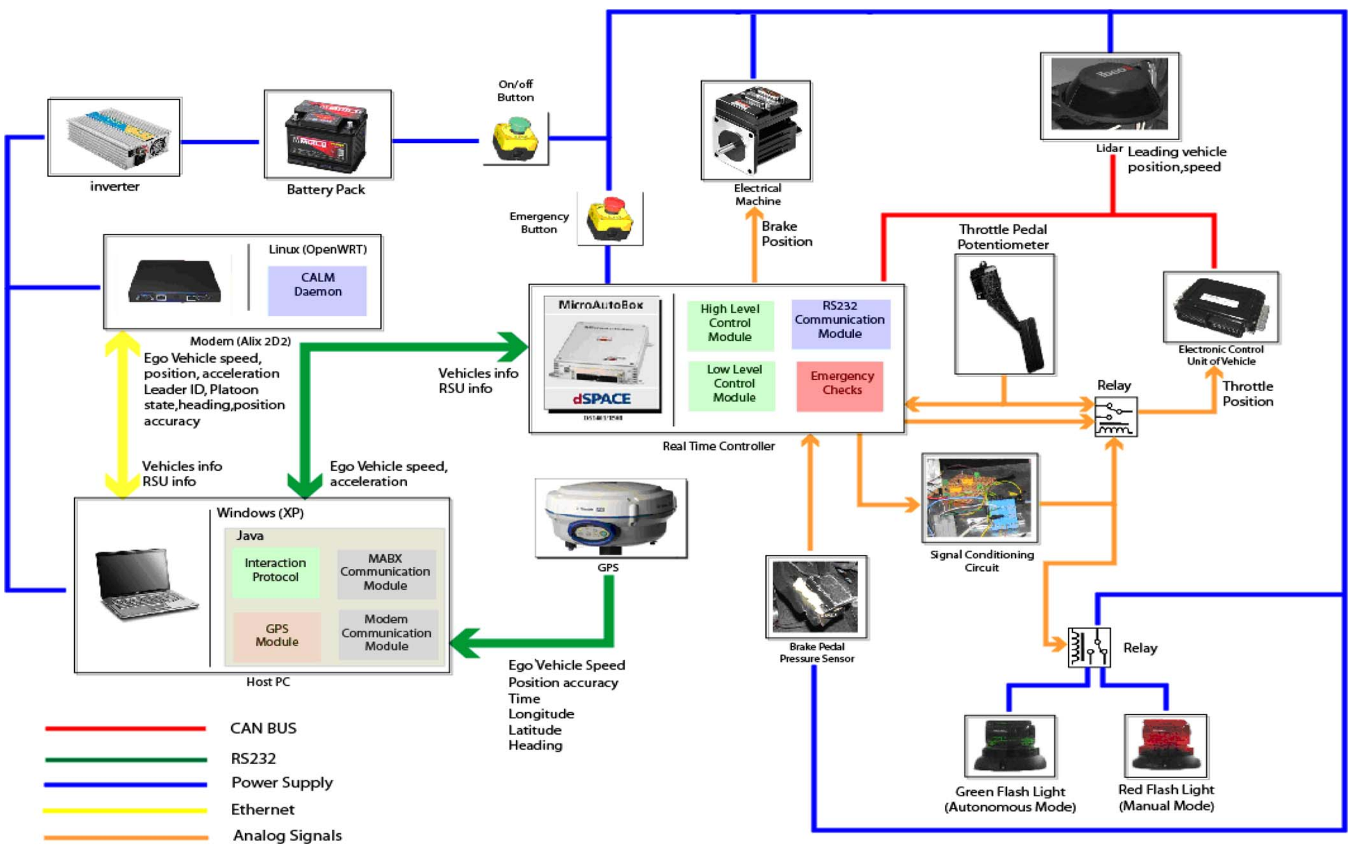

Fig. 3. Information flow in the Team Mekar vehicle semiautonomous system.

interface is used to actuate the brake pedal based on commands from the low-level controller.

The low-level controller receives its gas pedal (throttle) and brake pedal (braking) commands from the higher level CACC algorithm, also running in the dSpace microautobox. The low-level controller is a throttle or brake controller. The control law used generates an acceleration request, which is then converted to a suitable throttle or brake command. The acceleration request level is determined by the comparison of the desired and actual accelerations. Positive acceleration requests result in increased throttle. Negative acceleration requests result in reduced throttle up to a certain predetermined level in case the throttle input is not zero to begin with. Negative acceleration requests below this predetermined level result in braking.

A brake pedal force sensor is mounted on the brake pedal, as shown in Fig. 2, for determining manual braking action/request by the driver. Once manual braking is detected by sensing the force signal on the brake pedal, the smartmotor shown in Fig. 2, which autonomously actuates the cable connected to the brake pedal, goes to its home position, thereby loosening the cable connection and transferring control of the brake back to the driver. The driver can always override the autonomous CACC system by pressing the gas or brake pedals. The position of the gas pedal is read from the vehicle CAN bus through the dSpace microautobox controller. An emergency stop button is also placed between the driver and front passenger seats. When the driver presses either the gas or brake pedals or the emergency stop button, control authority is transferred from the autonomous controller back to the driver, and the red light on top of the vehicle lights up and stays lit. During autonomous operation, the green light on top of the vehicle stays lit.

The vehicle is equipped with an Alasca Ibeo 4 layer lidar placed in front of the vehicle, which was used for collision avoidance with the preceding vehicle. The electronic control unit of the lidar detects and tracks the preceding vehicle and sends relative distance and speed information to the dSpace microautobox low-level control unit. The longitudinal acceleration value read from the vehicle CAN bus is communicated through the V2V system in the CACC implementation. The main sensor on the Team Mekar vehicle is a real-time kinematic (RTK) GPS sensor (see Fig. 2). The Team Mekar vehicle's high-precision position and heading information at 10 Hz was provided by this RTK GPS sensor, which was preprogrammed based on the specifications of the TNO RTK base station. The upper highway speed limit of 80 km/h (approximately 22 m/s) in the GCDC heats will result in a 2.2-m travel distance within the 0.1-s GPS update time. This is, of course, a problem for Team Mekar, which had to implement communicated-GPS position-based ACC/CACC in the GCDC runs. The standstill distance used in the GCDC runs ranged from 10 m to 15 m, depending on the participant. Even at a 10-m standstill distance, this inter-GPS sample travel of up to 2.2 m at high speeds was not a critical problem. Although it was not possible during the GCDC, the current approach to CACC of Team Mekar is also based on combining radar- or lidar-based ACC with V2V communication. The interesting result of Team Mekar's

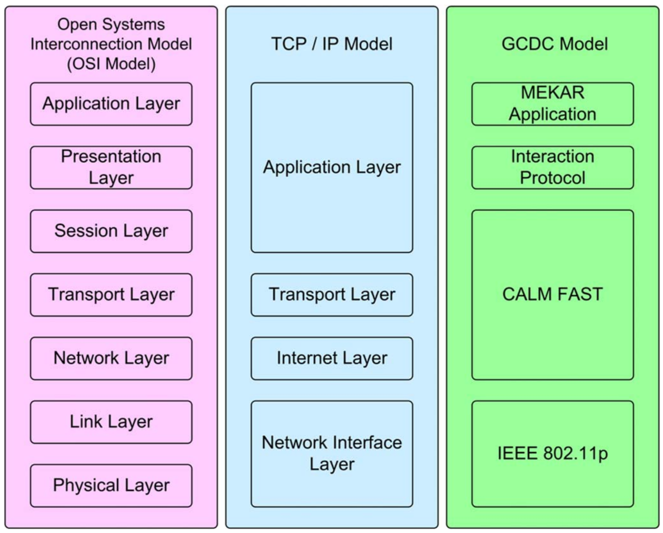

Fig. 4. GCDC communication model, TCP/IP Internet model, and OSI reference model comparison.

having to use a communicated-GPS-only system for CACC was that acceptable performance was obtained at a 10-Hz GPS update rate. Faster GPS update rates such as 100 or 250 Hz are available in commercially available GPS/IMU integrated systems. At an update rate of 100 Hz, the vehicle travel time in 0.01 s at a speed of 22 m/s is 0.22 m. At an update rate of 250 Hz, the vehicle travel time at a speed of 4 ms is 0.08 m. These numerical values demonstrate that communicated-GPS/IMU position/velocity information can be feasible in future ACC/CACC systems, depending on a reduction in price of the fast GPS/IMU units.

Note that the accuracy of the relative position parameter is based not only on the GPS update frequency. It also depends on the accuracy of the GPS position determination and the latency involved, including the V2V communication frequency and delay. The bandwidth of the longitudinal dynamics of the vehicle, i.e., how fast it responds to throttle and brake commands, is also not so fast. Taking these factors into account, a GPS update rate of 10 Hz will be sufficient for communicated-GPS based ACC/CACC implementation. A faster sampling rate based on GPS integrated with IMU measurements will improve the position change between samples at higher vehicle speeds.

The most critical equipment for the GCDC challenge was the communication hardware. The hardware for 802.11p communication, which consists of the ALIX2D2 Board and Atheros-based wireless local area network (WLAN) card Microtik Routerboard R52H, was provided by TNO to the participants of GCDC. As shown in Fig. 4, the IEEE 802.11p protocol specifies the physical layer and the data-link layer of the Open Systems Interconnection (OSI) reference model. The layers from the network up to the session layer are covered by the Communications Access for Land Mobiles (CALM) protocol. The CALM protocol runs on the lightweight Linux environment OpenWRT using raw sockets. Unlike the Transmission Control Protocol/Internet Protocol (TCP/IP) model, the CALM protocol was used with broadcasting messages. Similar to communication hardware, the files necessary to compile the

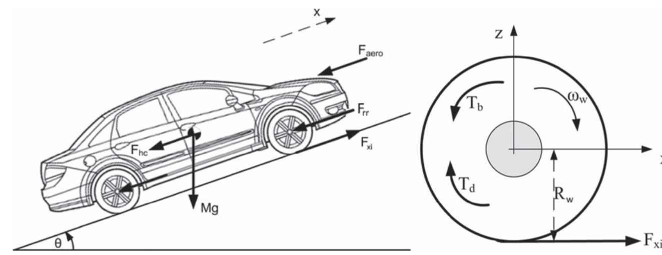

Fig. 5. Longitudinal vehicle dynamics model.

OpenWRT operating system and the CALM protocol files and patches for the Linux wireless driver ath5k were provided by the GCDC organization. The GCDC interaction protocol was published by TNO in Abstract Syntax Notation One (ASN.1) format. ASN.1 specifications determined the format and timing of GCDC messages. The Java environment was chosen, because it worked without problems, and Java code is highly portable.

III. Longitudinal Vehicle Model

A longitudinal vehicle dynamics model and single and double track Simulink models with longitudinal dynamics and a CarSim model of the Team Mekar vehicle were prepared for controller design and simulation studies. The vehicles in the GCDC are autonomous in the longitudinal direction only, through automated throttle and braking based on the CACC system. Steering is manually controlled. Hence, the longitudinal modeling presented in this section is enough for CACC algorithm development and testing.

The free-body diagram of the longitudinal dynamics of a vehicle moving on an inclined road is shown in Fig. 5. To propel the vehicle using traction force F_t, resistive forces such as rolling resistance F_{rr}, aerodynamic drag F_{aero}, and gravitational slope resistance F_{hc} should be overcome according to

$$\begin{aligned} &M\ddot{x} = F_{xi} - (F_{aero} + F_{rr} + F_{hc}) \\ &F_{xi} = F_d \text{ (driving or traction)}, \quad F_{xi} = -F_b \text{ (braking)}. \end{aligned} \tag{1}$$

F_{xi} is the tire longitudinal force, which becomes F_d during driving and $-F_b$ during braking. The aerodynamic drag force F_{aero} is given by

$$F_{aero} = \frac{1}{2} A\rho C_D v^2 \tag{2}$$

where A is the effective frontal area of the vehicle, ρ is the mass density of air, C_d is the drag coefficient, and v is the speed of the vehicle relative to the air speed. The rolling resistance force F_{rr} is modeled as

$$F_{rr} = C_{rr} M g \cos(\theta) \tag{3}$$

and is linearly proportional to normal force acting on tires, with M representing the vehicle mass. C_{rr} in (3) is the rolling resistance coefficient. The gravitational slope resistance force F_{hc} is given as

$$F_{hc} = M g \sin(\theta). \tag{4}$$

In the vehicle model, the vehicle mechanical driveline is modeled as rigid bodies, with losses modeled by efficiencies and transmission gear ratio values. The transmission is modeled as a selectable transmission ratio i_t, and a static efficiency factor η_t is used to model mechanical losses. The internal combustion engine (ICE) is modeled using a static torque map that defines the relationship between the inputs of throttle position α and engine speed ω and the output engine torque T_{ICE}. The throttle input comes from either the driver gas pedal during manual operation or from the CACC low-level control system during autonomous operation. The torque output from the static map of the ICE is transmitted to the wheels through the driveline as torque T_d as

$$T_d = \eta_t i_t T_{ice}(\omega, \alpha). \tag{5}$$

The free-body diagram of a single wheel is illustrated in Fig. 5, right-hand side. The moment balance at the center of the wheel results in

$$I_{wi}\dot{\omega}_w = T_d - T_b - F_{xi}R_w \tag{6}$$

where I_{wi} is the moment of inertia of the wheel, ω_w is the wheel angular velocity, $\mathrm{T_b}$ is the braking torque applied through the brake system, R_w is the effective wheel radius, and the longitudinal tire force is $F_{xi} = F_d$ for driving and $F_{xi} = -F_\mathrm{b}$ for braking.

IV. Cooperative Adaptive Cruise Control Implementation

A. CACC System and Simulations

The Team Mekar CACC implementation consists of higher level event-based control architecture and a lower level CACC algorithm. A basic outline of the Team Mekar control architecture is schematically illustrated in the flowchart in Fig. 6. In the CACC operation, the V2V modem continuously sends the required static and dynamic information about the vehicle and listens to the communication from the other vehicles and the RSUs. The location of the other vehicles is determined in the high level control algorithm. The higher level control algorithm also makes decisions on joining platoons and stopping at traffic lights (not illustrated in Fig. 6). The standstill separation distance and the desired headway time are entered into the overall CACC implementation by the operator. The ACC part of the CACC algorithm calculates a desired acceleration using a PD-type control law on position and velocity errors. The desired acceleration is compared with the allowed maximum deceleration of -4 m/sec^2 and the allowed maximum acceleration of 2 m/sec^2. The desired acceleration is converted to corresponding engine or brake torque values and then to corresponding throttle or brake actuator signals, which are sent to the low-level throttle or brake controllers.

The Team Mekar CACC approach is based on previous work on ACC in [13]–[15] and CACC in [17]–[19]. To be compatible with the rest of the teams and the rules, the Team Mekar high-level CACC implementation was based on the approach presented in [12], which is illustrated for two cooperating vehicles in Fig. 7. G_i represents the vehicle dynamics of the ith vehicle. K_i and F_i represent the feedback and feedforward controllers of the ith vehicle, respectively. H_i is the spacing policy dynamics, and D_i represents the communication delay of the ith vehicle.

With regard to the vehicle dynamic model, the automated brake system was tested by applying step brake changes of different amplitude and swept sine testing. Model identification resulted in a first-order brake system model, which was validated against experimental data. This first-order model accurately captured the time constant of brake system pressure changes in response to changes in brake command. Chassis dynamometer testing was used to create an engine torque map from the throttle command input and engine speed to engine torque at the tire level.

The simulation of a convoy that consists of a lead vehicle and four CACC-equipped following vehicles is formed by adding more vehicle models. The feedback controller K_i $(i = 2)$ given by

$$K_i(s) = K_{p,i} + K_{d,i}s \tag{7}$$

in Fig. 7 is a PD-type controller that was designed using the linear–quadratic regulator approach, as shown in [20]. The feedforward controller F_i $(i = 2)$ in Fig. 7 is designed using the approach in [12] and is given by

$$F_i(s) = \frac{\tau_i s + 1}{\tau_{hw} s + 1} \tag{8}$$

where τ_{hw} is the desired headway time, and $1/\tau_i$ is the desired closed-loop bandwidth.

Speed profile following and CACC platoon simulations were carried out after the GCDC using the Team Mekar vehicle's CACC implementation and its validated vehicle model. The results displayed in Fig. 8 demonstrate satisfactory tracking of the desired speed profile. The time headway regulation achieved in the simulations is shown in Fig. 9. It is shown that the desired headway time regulation of 0.6 s is reached with a maximum headway time error of about 0.2 s (at speeds around 10 m/s, giving rise to a headway distance error of 2 m). The largest headway regulation errors occurred at two instances: one instance is close to 100 s, and the other instance is between 150 and 200 s. These peaks in headway regulation error corresponded to sudden speeding portions of the speed profile. Hardware-in-the-loop simulations with the two V2V modems that correspond to a lead vehicle and a follower vehicle were also carried out. The results were similar to the results in Figs. 8 and 9.

B. Analysis of Team Mekar GCDC 2011 Results

Before taking part in the GCDC heats, the Team Mekar vehicle passed a last test in the DAF test track, where the speed profile communicated by the TNO lead vehicle was followed. The result displayed in Fig. 10 show that there is large overshoot in the beginning compared to no overshoot in the simulated response in Fig. 8. There are two reasons for this case. One reason is the high sampling time that had to be used during that test, resulting in worse controller performance than

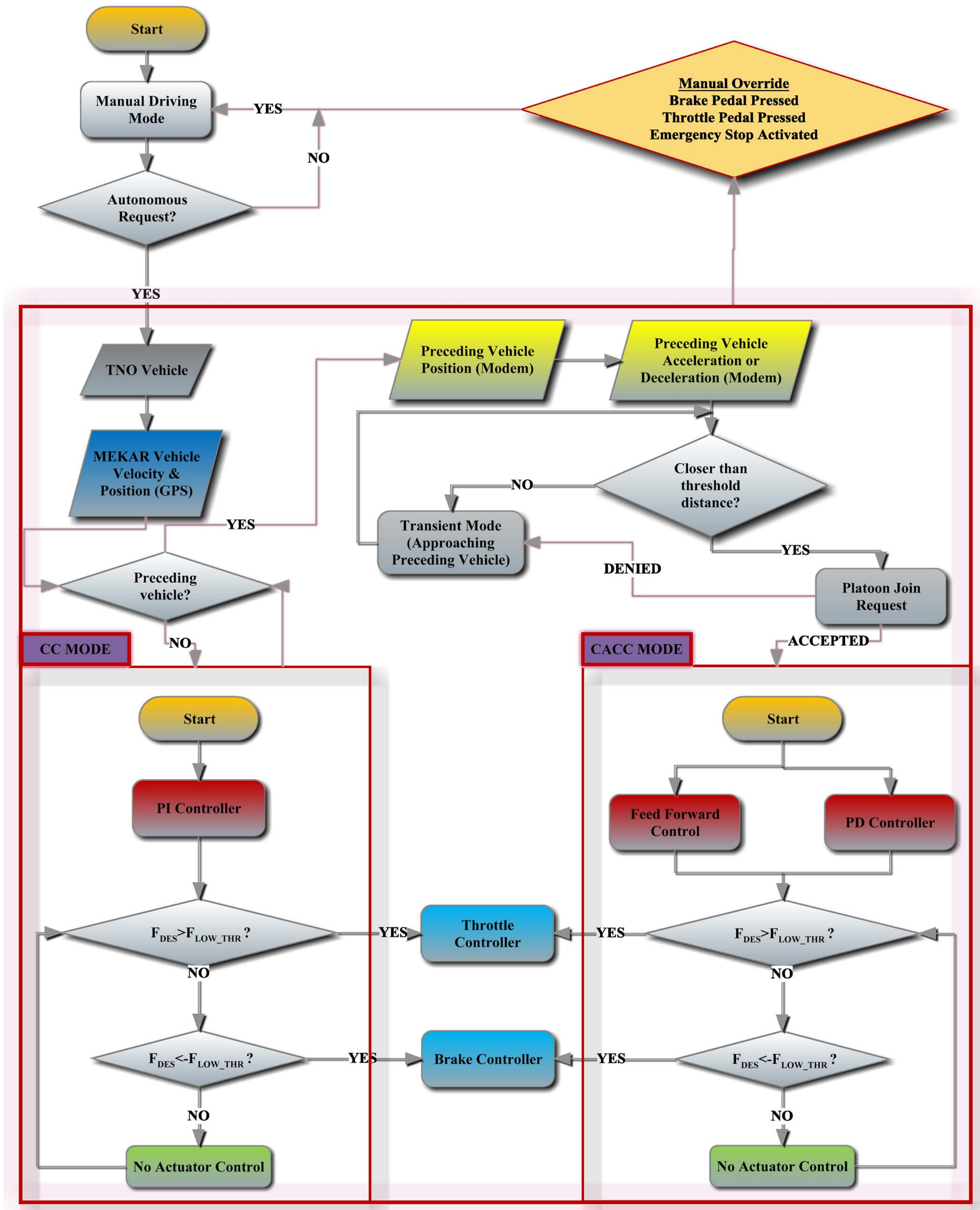

Fig. 6. Outline of the architecture of CACC in the Team Mekar GCDC vehicle.

expected. The other important reason is that the Team Mekar CACC/ACC implementation does not have control of the built-in automatic transmission controller. The automatic transmission shifts to higher gear at around 60 km/h, and the vehicle cannot accelerate fast enough until 80 km/h; thus, a slow speed increase from 60 km/h to 80 km/h is observed. Once 80 km/h

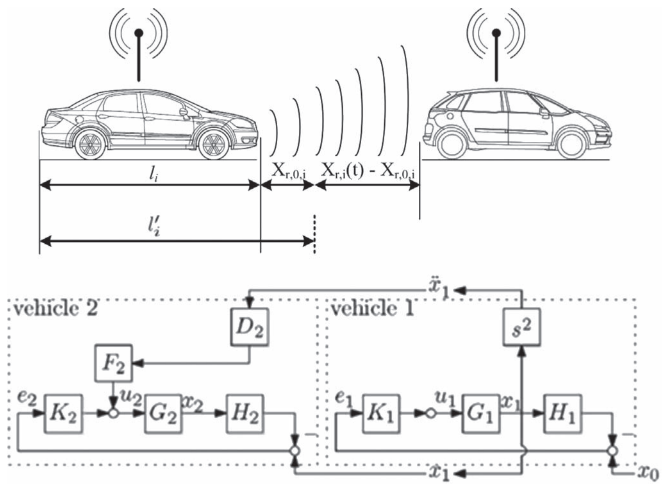

Fig. 7. CACC implementation with two vehicles [12].

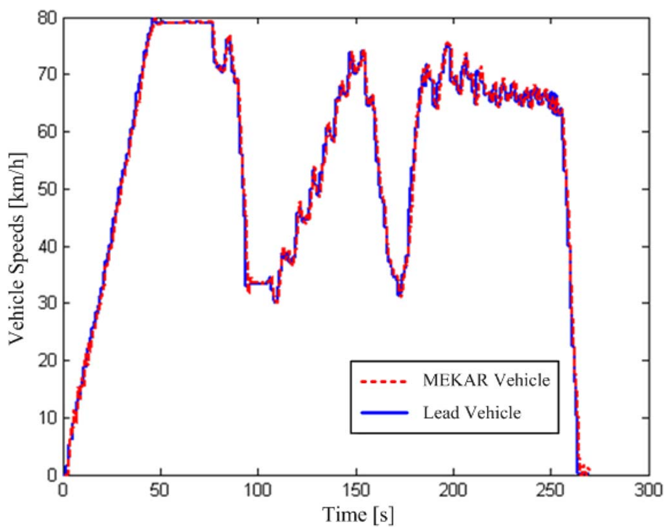

Fig. 8. Team Mekar CACC implementation speed profile following simulation.

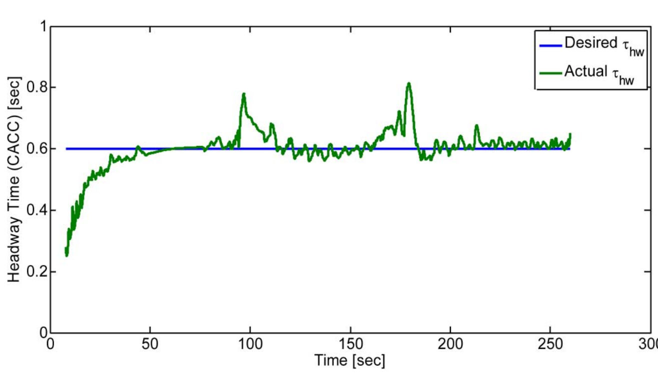

Fig. 9. Team Mekar CACC implementation headway time regulation simulation.

is reached and exceeded, the vehicle is already accelerating, and the controller first tries to slow down by reducing throttle. However, the vehicle cannot decelerate fast enough, because it is already at high gear, which is not automatically shifted down. Thus, the vehicle speed keeps increasing, but at a lower rate up to about 88 km/h, as shown in Fig. 10. Then, brake control takes

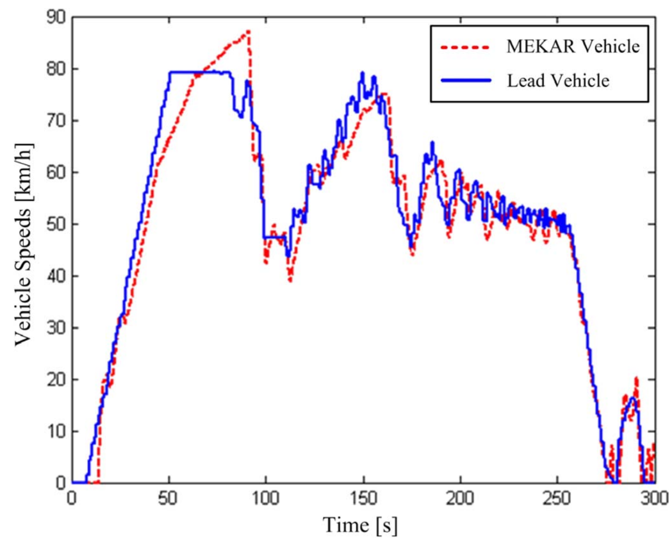

Fig. 10. Following speed profile communicated by the lead vehicle in the DAF test track.

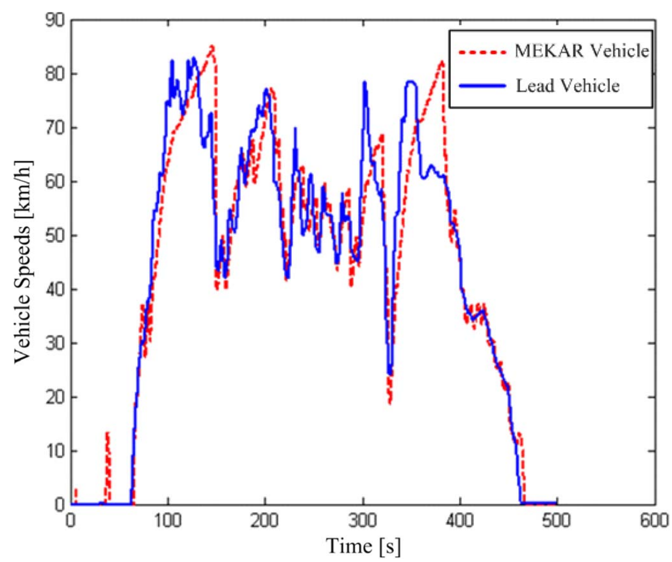

Fig. 11. Following speed profile communicated by the preceding vehicle in the convoy test in the DAF test track.

over, which shows as a sudden decreasing of speed after a peak speed of about 88 km/h.

The Team Mekar vehicle later took part in the convoy with the other GCDC participants in the DAF test track. A similar but less evident trend is shown in the second DAF test track result, as shown in Fig. 11. This is an acceptable but not highly satisfactory result, which shows how the Team Mekar vehicle followed the speed profile communicated by the preceding vehicle in the convoy.

A change in the negative acceleration request level that was used for switching from throttle reduction to brake control resulted in relatively better overshoot performance in the GCDC test run results, as shown in Figs. 12 and 14 and later in this section. The CACC gains were also retuned, and some adjustments were made before the GCDC heats. The results in Figs. 12 and 13, which correspond to the first and second GCDC heats, exhibit better performance in the form of less overshoot

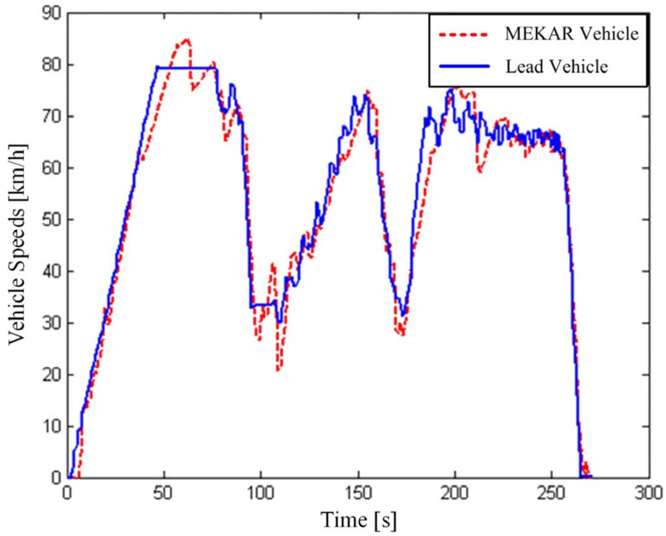

Fig. 12. Team Mekar speed following performance in a GCDC heat.

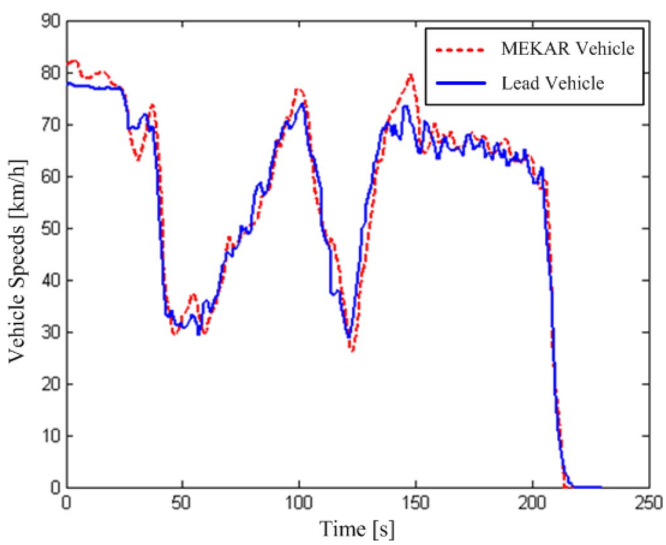

Fig. 13. Part of Team Mekar speed following performance in a GCDC heat. The first part of the data was not recorded.

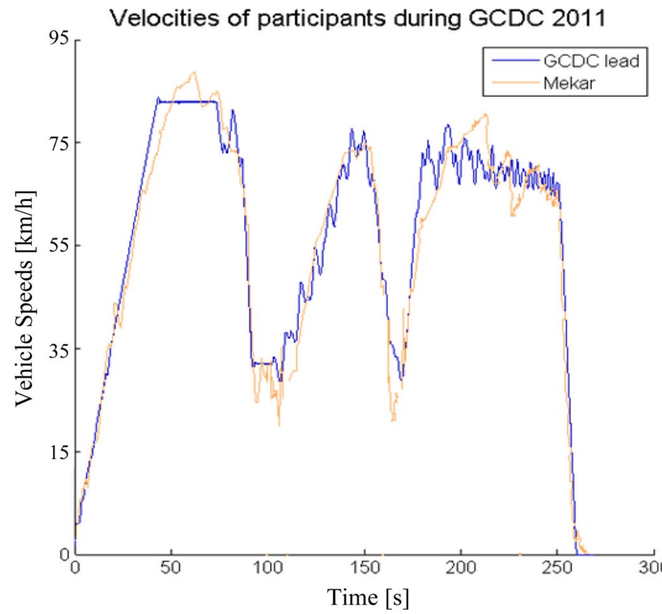

Fig. 14. Speed profile during a GCDC heat, provided by TNO.

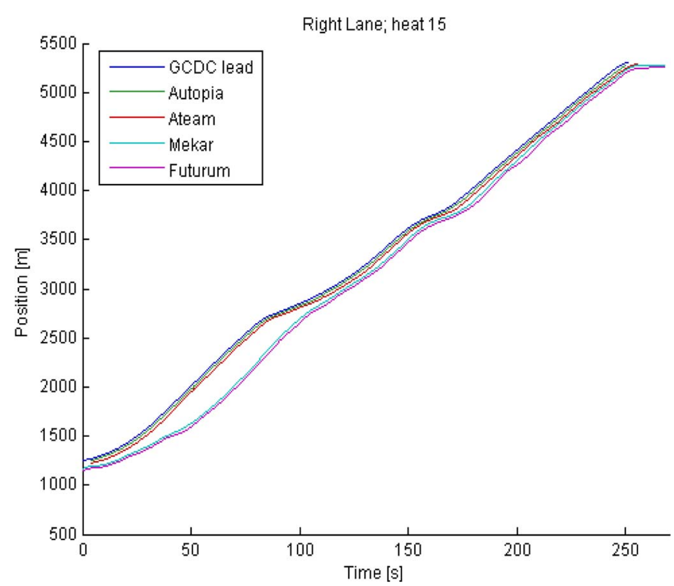

Fig. 15. Vehicle positions during a GCDC heat, provided by TNO.

and less tracking error, particularly in following the higher frequency desired speed variations compared to the results in Figs. 10 and 11.

An experimental speed profile that was provided by TNO after the GCDC from a GCDC heat in which Team Mekar was the first vehicle after the TNO lead vehicle is shown in Fig. 14. The speed following performance in terms of tracking error in Fig. 14 was not as good as in the previous GCDC heat test results, because the CACC system operated at a higher sampling time on that test. A GCDC heat separation plot is shown in Fig. 15. At the beginning of that heat, the Team Mekar vehicle did not travel at the correct highway speed limit of 80 km/h due to a software error. Thus, the Team Mekar vehicle could not accelerate to catch up with the rest of the convoy in the beginning, because its maximum speed was limited. This problem was later fixed in the heat, and the Team Mekar and the following vehicle, having formed their own convoy, sped up and merged with the convoy in front. The headway time used in the test in Fig. 15 was 1 s.

Fig. 16 shows a position plot of ten simulated vehicles with color-coded vehicle acceleration. The large deceleration values and how they spread in the platoon are shown with blue color coding at positions where the lead vehicle suddenly decelerates. Shockwaves occur as a result of sudden speed changes of the lead vehicle. Investigation of the propagation of the shockwave in the platoon and how it is damped requires taking a look at the data of all vehicles in the platoon. The experimental results in Fig. 15 and the simulation results in Fig. 16 demonstrate that the platoon of vehicles with CACC keep proper intervehicle spacing. Shockwaves that were introduced by the lead vehicle are damped, except for the period between 100 and 200 s.

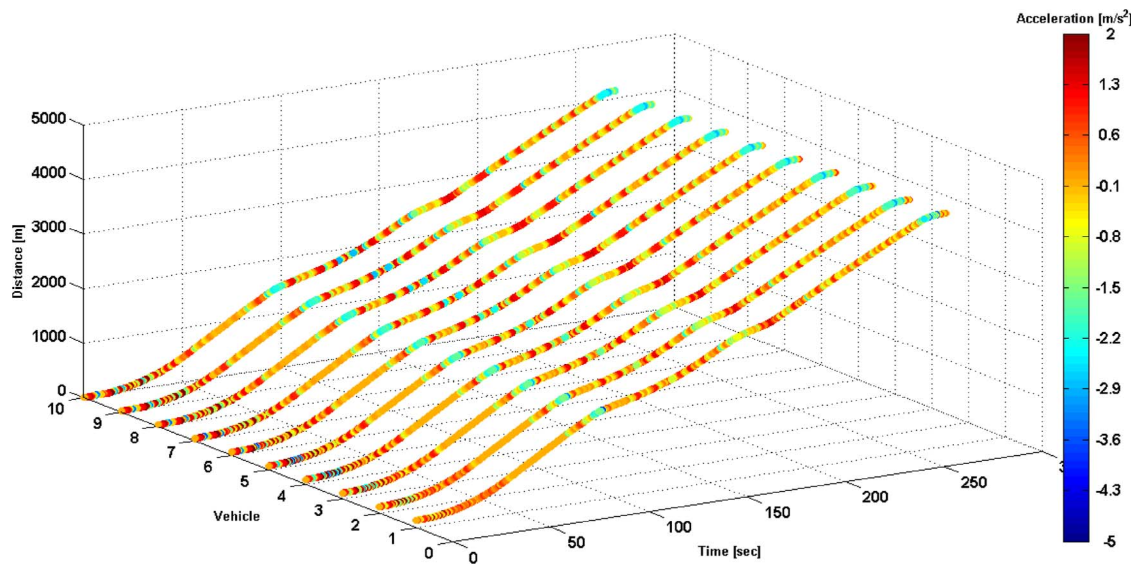

Fig. 16. Team Mekar CACC platoon simulation with color-coded acceleration.

Fig. 17. Service road around the Formula 1 Istanbul park circuit.

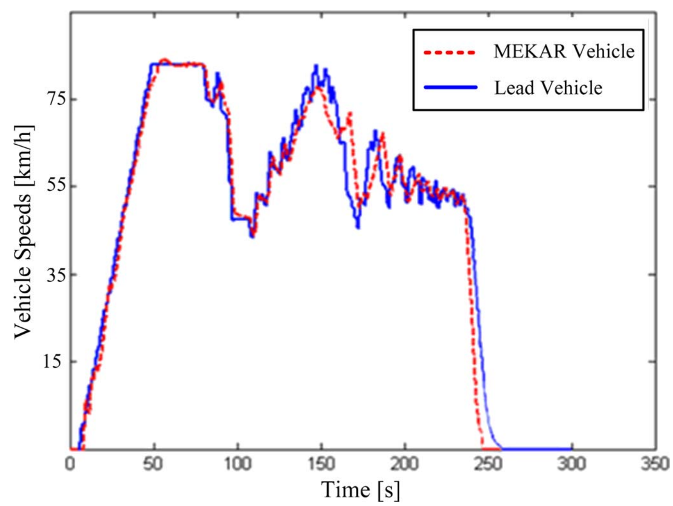

Fig. 18. Speed profile following test after the GCDC.

C. Road Tests After the GCDC

The speed profile following test of the GCDC was repeated on the service road around the Formula 1 Istanbul Grand Prix circuit, because it was the longest stretch of closed road that we could find. We were able to use about 4.5 km of that road, which is highly different from the flat 6 km of road used on the A270. Compared to A270, this service road, as shown on the map in Fig. 17, has high curvature, which means larger steering action by the driver, and large uphill and downhill slopes. The CACC system in the Team Mekar vehicle was kept the same as in the GCDC, with the only difference that it used a higher sampling rate. The low-level control functions (brake and throttle) that were designed as continuous-time controllers and should have been implemented at a high sampling rate accidentally operated at a low sampling rate down to 1 Hz during some of the heats due to problems of hardware/software during the GCDC. In the post-GCDC trial, the low-level brake/throttle controls ran at faster sampling.

The experimental results in Fig. 18 demonstrate better speed profile following. The parts where the speed profile seems to lag the desired profile correspond to upward slopes where the Team Mekar GCDC vehicle with a relatively small engine had difficulty in speeding up fast enough. The first large drop in actual velocity corresponds to the end of the service road where the driver intervened and autonomous driving was stopped. This result was promising, because it demonstrated that, at least, the speed profile following part of our CACC implementation satisfactorily worked in curved and sloped roads, which are typical in Turkey.

D. Scientific Lessons Learned

The scientific lessons that we learned during the GCDC are listed as follows.

- Adding ACC and CACC systems to a vehicle requires access to the automatic transmission control system to reach satisfactory performance in case of a sudden acceleration requirement.
- Starting with a vehicle that is not fitted with ACC by an original equipment manufacturer requires too much effort devoted to incorporating ACC into the vehicle and then upgrading to CACC. It is best to start with an ACC fitted vehicle.

- CACC implementation built on top of an existing ACC system is both technically and economically feasible (the longitudinal acceleration signal is already available due to the electronic stability control unit, and IEEE 802.11p modems are relatively cheap).
- Two vehicles are necessary for research work on developing and testing CACC systems. The first vehicle can be a nonautonomous lead vehicle.
- Cooperative driving of platoons of vehicles of different make and size is possible using CACC with IEEE 802.11p communication.
- It is possible to successfully implement ACC and CACC based on communicated GPS positions. An accurate GPS with an integrated IMU with fast update (100 Hz, for example, although a 10-Hz update rate will also be sufficient for successful implementation) is recommended in this approach. This is, of course, only possible when all vehicles in the platoon have V2V communication capability. If vehicles without V2V communication enter the platoon, a radar or lidar still has to be used for ACC purposes.
- Proper choice and positioning of the V2V communication antenna is very important. Larger vehicles may need more than one antenna. One vehicle had problems with communication due to the positioning of its antenna, which means that the Team Mekar vehicle had both ACC and CACC problems when directly following that vehicle in a convoy.
- One vehicle did not send its acceleration information to the following vehicle in the GCDC runs, which means that Team Mekar had only ACC and not CACC based on V2V communication while following that vehicle. This case was shown as an advantage of CACC, because it becomes an ACC controller in the absence of feedforward of the preceding vehicle acceleration.

V. Conclusion

This paper has shown that taking part in the GCDC was a very useful experience that allowed Team Mekar to pinpoint problems and weaknesses for more successful future implementations. The GCDC itself was a success, because it demonstrated that cooperative mobility with teams from different countries and vehicles from different vendors, ranging from a compact vehicle to a heavy duty truck, all using the same IEEE 802.11p protocol, can successfully be implemented. Future more demanding demonstrations such as the GCDC will make it easier for the public to accept emerging cooperative mobility applications such as CACC.

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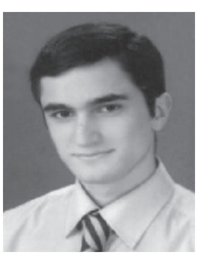

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