The Grand Cooperative Driving Challenge 2016: Boosting the Introduction of Cooperative Automated Vehicles

Cristofer Englund, Lei Chen, Jeroen Ploeg, Elham Semsar-Kazerooni, Alexey Voronov, Hoai Hoang Bengtsson, and Jonas Didoff

Abstract

The Grand Cooperative Driving Challenge (GCDC), with the aim to boost the introduction of cooperative automated vehicles by means of wireless communication, is presented. Experiences from the previous edition of GCDC, which was held in Helmond in the Netherlands in 2011, are summarized, and an overview and expectations of the challenges in the 2016 edition are discussed. Two challenge scenarios, cooperative platoon merge and cooperative intersection passing, are specified and presented. One demonstration scenario for emergency vehicles is designed to showcase the benefits of cooperative driving. Communications closely follow the newly published cooperative intelligent transport system standards, while interaction protocols are designed for each of the scenarios. For the purpose of interoperability testing, an interactive testing tool is designed and presented. A general summary of the requirements on teams for participating in the challenge is also presented.

Introduction

In 2011, nine international teams joined the Grand Cooperative Driving Challenge (GCDC), with the purpose of supporting and accelerating the introduction of cooperative and automated vehicles in everyday traffic through a driving challenge. The challenge was to perform collaborative platooning where vehicles drive in road trains with short inter-vehicular distance to save fuel, and improve safety and throughput.

Since then, cooperative vehicles have become a hot topic, and several projects have shown advanced platooning capabilities based on single-vendor solutions such as SARTRE [1]. Today, car makers are constantly adding new automated features to support safety and to increase comfort for drivers and passengers. In this context, two parallel and overlapping areas, cooperative vehicles and autonomous vehicles, emerge and need to be distinguished. Cooperative vehicles build on collaboration through communication, whereas autonomous vehicles have the ability to drive with only the support of onboard proximity sensors. Integration of the two results in cooperative and automated vehicles.

In 2014, the European standardization organizations, the European Committee for Standardization (CEN) and European Telecommunications Standards Institute (ETSI), confirmed the finalization of the first set of standards on C-ITS [2], which brings cooperative inteligent transport systems (C-ITS) closer to deployment. With the purpose of showcasing the benefits of C-ITS and accelerate its deployment in realistic traffic, the new edition of GCDC takes cooperative automated driving one step further by integrating interoperable wireless communication and advanced manoeuvers, allowing automated lateral and longitudinal control. Focusing on the multi-vendor implementation and interoperability, and based on close-to-reality scenarios, the challenge provides an environment to showcase the latest advancements in cooperative automated vehicles. GCDC is in conjunction with other autonomous vehicle competitions, such as the Defense Advanced Research Projects Agency (DARPA) Urban Challenge in 2007,[1] focusing on the cooperative aspects of driving rather than autonomy.

Experiences from GCDC2011

In GCDC2011, two scenarios, one urban and one highway, were performed. The urban scenario featured two platoons standing one after the other with a certain distance. The task was to let the rear platoon join the foremost platoon with minimum disturbances. The highway scenario focused on platooning performance, where a lead vehicle from the organizers guided the participating vehicles in manoeuvers (Fig. 1).

For both scenarios, evaluation criteria were based on total platoon length, platoon length variations, vehicle gap length, and string stability, that is, the capability of the vehicles to attenuate the effects of acceleration disturbances. The vehicles incorporated automated longitudinal control, whereas the drivers manually operated the lateral steering. GCDC2011 focused on forming platoons. While basic platoon operations such as join from rear on a single lane were per-

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[1] http://archive.darpa.mil/grandchallenge/

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formed, complicated operations such as platoon merge from two parallel lanes were out of reach. A leading vehicle (e.g., the platoon leader) was used to broadcast maneuvering information and control all platoon members.

Many challenges surfaced during GCDC2011, ranging from different interpretation of standards (e.g., time and position) to issues with radar reflections [3–8]. One of the main challenges that occurred was related to wireless communication, where all participants should interpret the transmitted information in the same way. These issues naturally lead to interoperability among vendor-dependent implementations, which is essential to manage the introduction of cooperative vehicles in realistic traffic.

Expectations for GCDC2016

GCDC2016[2] aims at demonstrating how cooperative and automated vehicles can perform complicated platooning operations with close-to-reality traffic scenarios. While GCDC2011 focused on basic platooning such as forming and maintaining a platoon, in GCDC2016, the capability of platooning is considered as a prerequisite. The focus moves to the cooperative aspects, where advanced platoon operations (e.g., cooperative merge of two parallel platoons) will be demonstrated. In addition, GCDC2016 introduces a cooperative intersection scenario to demonstrate how cooperative vehicles solve complicated intersection scenarios safe and efficiently. Furthermore, a demonstration scenario is considered to show how C-ITS can help to create free passage for emergency vehicles. It is expected that through GCDC2016:

- The introduction of platooning to realistic traffic will be accelerated.
- The cooperative automated manoeuvers enabling complex platooning operations will be showcased.
- The introduction of cooperative intersection management through C-ITS will be accelerated.
- The benefits of C-ITS for addressing realistic traffic challenges such as roadworks and emergency vehicles will be demonstrated.
- The public awareness of C-ITS for improving traffic safety, efficiency, and sustainability will be improved.
- The benefits and issues will be investigated that will contribute to the next release of C-ITS standards.

Scenarios

The main idea of GCDC is to boost the introduction of cooperative and automated driving. The chosen scenarios consider both the current development within C-ITS, the suggestions from domain experts, as well as the proposals from the participating teams. Two typical environments are considered: the highway and the intersection. The scenarios are chosen to focus on the cooperative aspects with consideration to the basic set of applications (BSA) in C-ITS standards, as well as a potential extension to the forthcoming enhanced set of applications (ESA).

While basic platooning was demonstrated in GCDC2011, advanced platoon operations (Fig. 2) need to be investigated further to support

Figure 1. Photo from GCDC2011.

future development. The cooperative platoon merge scenario involves two platoons driving on a motorway on different lanes that must merge into one platoon due to an upcoming construction site where one lane is closed. A competition zone (CZ) is defined within which the vehicles' operations will be judged. The scenario includes common events on road traffic including road works, lane closure, traffic merge, and so on. All events are expected to be resolved efficiently through communication and collaboration between vehicles. Furthermore, advanced platoon operations will be performed while showcasing a very relevant scenario in future traffic.

Intersections are one of the most critical and challenging traffic environments that are attracting significant work [9]. In order to showcase the C-ITS benefits, the cooperative intersection scenario considers a very common urban traffic situation (i.e., uncontrolled intersections). To be more realistic for near future deployment, this scenario involves a mixture of non-cooperative (not communicating) and cooperative vehicles. As shown in Fig. 3, one cooperative vehicle is approaching a busy two-lane road with vehicles driving in both directions. The approaching vehicle transmits its intention, to turn left at the intersection, and cooperative vehicles on the main road acknowledge its request and help to facilitate the intersection passing. Consequently, the vehicles on the main road help to create proper gaps, allowing smooth passage for the left-turning vehicle and thus improving traffic safety and efficiency.

The third scenario includes an emergency vehicle that requires passage in a congested traffic situation. This is a demonstration scenario and considers an everyday traffic event that needs efficient solutions. Emergency vehicle

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[2] It is acknowledged that the term GCDC 2016 is cross-used with i-GAME as the 2016 challenge organized by the project i-GAME.

GCDC2016 introduces a unique opportunity to showcase development in a distributed and collaborative environment. It is a mixture of competition and collaboration, as all scenarios require close cooperation among teams through wireless communication, while full flexibilities are given to the teams in respect to confidential areas such as control systems.

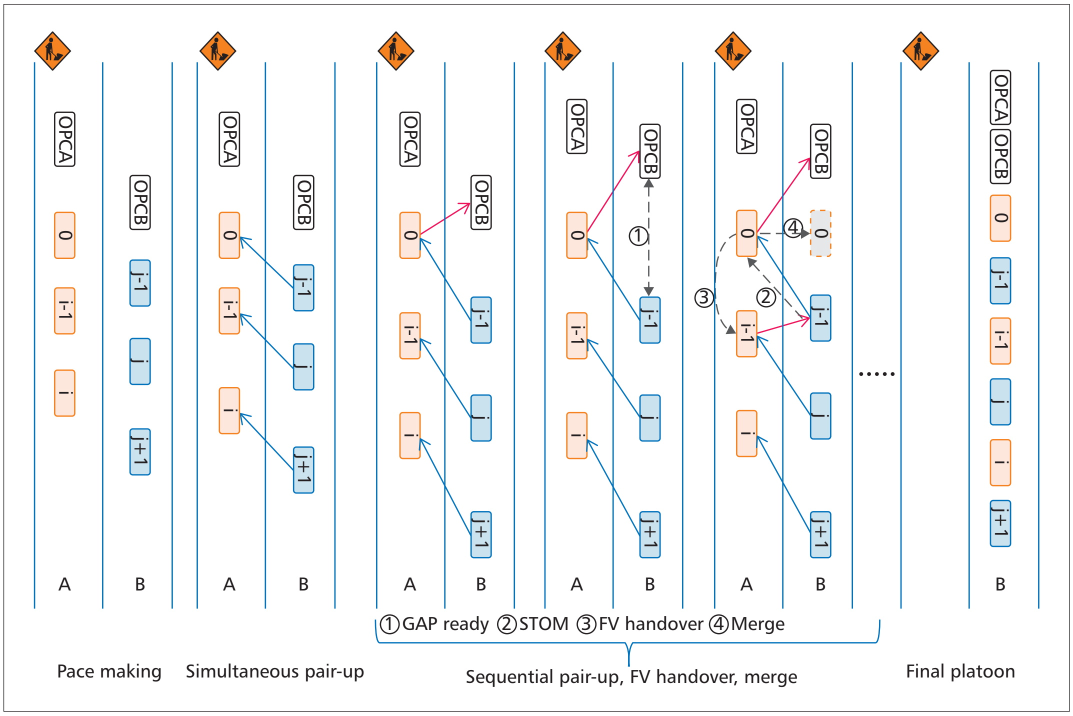

Figure 2. Scenario illustration and interaction process of cooperative platoon merge.

warning has been considered in both the BSA of C-ITS and in the context of autonomous vehicles [10]. However, the current version provides only a warning of the emergency vehicle, and the often perceived confusion on where to place the vehicle is not alleviated. With the proposed amendments, the emergency vehicle will be able to inform other vehicles of its itinerary and how it wants other vehicles to behave, thereby providing free and safe passage.

All of the above scenarios demonstrate situations where cooperative and automated vehicles can bring significant benefits to road traffic. In this regard, GCDC2016 is far more challenging than its predecessor. The challenge is two-fold. Technically, it is challenging to develop and implement functions for cooperative automated vehicles, and organizationally it requires versatility to allow a multi-vendor group of vehicles to communicate and exchange messages that need interpretation and correct interaction.

GCDC2016 introduces a unique opportunity to showcase development in a distributed and collaborative environment. It is a mixture of competition and collaboration, as all scenarios require close cooperation among teams through wireless communication, while full flexibilities are given to the teams in respect to confidential areas such as control systems. This is also the situation where vehicle manufacturers find themselves in developing cooperative automated vehicles.

Communication and Interaction

Cooperative ITS

In C-ITS, a common architecture for vehicles, the roadside unit, and the traffic management center is introduced, that is, the so-called ITS station (ITS-S). As illustrated by Fig. 4, the radio access technology for C-ITS is ITS-G5, which works on the dedicated 5.9 GHz frequency band. For networking and transport protocol, the basic transport protocol (BTP) and GeoNetworking are proposed. In the facilities layer different services, such as the cooperative awareness (CA) service and the decentralized environmental notification (DEN) service, are specified, and the cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENMs) are defined. A CAM is the heartbeat message, which is broadcast periodically to surrounding vehicles with basic vehicle information, including speed, location, and so on. A DENM is event-based and is used for reporting road events, such as road work, accidents, and so on.

In i-GAME, radio equipment is based on the ITS-G5 specification, which has been available through major vendors and academia. For the upper layer protocols, an open source protocol stack[3] is developed including the BTP, GeoNetworking, as well as the CAM and DENM ASN.1 encoder and decoder. The protocol stack has been successfully tested for interoperability during an ETSI PlugTest. Standard CAM and DENM are used during the challenge. However, since they are mostly used for notifying existence and warning of events, these message sets do not fully support the implementation of the negotiation protocols aimed at distributed coordination between vehicles. Thus, a third message set is introduced, that is, the i-GAME Cooperative Lange Change Message (iCLCM)[4] set, and is broadcast by vehicles throughout the challenge. The iCLCM includes necessary information that is not available in CAM or DENM, and will be used for performing the interactions between vehicles during cooperative platoon merge and intersection passing. In i-GAME, the major ITS applications are the cooperative platoon merge, cooperative intersection passing, and emergency vehicle warning. In addition, other ITS applica-

[3] https//github.com/alex-voronov/geonetworking

[4] i-GAME Deliverable 3.2, http://cordis.europa.eu/docs/projects/cnect/5/612035/080/deliverables/001-D32.pdf

tions including roadwork warning, intersection collision warning, and so on will also be performed. It is acknowledged that security methods from the C-ITS standard are not considered for the challenge. Instead, the organization develops a comprehensive framework to ensure that the competition is performed in a safe and secure environment.

Interaction Protocol for Platoon Merge

For efficient and robust interaction, the i-GAME project designs an interoperable interaction protocol accompanied by communication message sets [11]. The interaction procedure of the platoon merge scenario consists of four phases: pace making, simultaneous pair-up, sequential pair-up, and merge. As shown in Fig. 2, there are two pace making cars, OPCA and OPCB, from the organization. They are not part of the challenge and are only responsible for setting up a proper scenario. The vehicles in platoons A and B are denoted by a_i and b_j, respectively. In Fig. 2, they are illustrated with their indices, i and j, only.

Pace Making: The two platoons are aligned and the speeds are synchronized. In addition, the first vehicle (FV) of platoon B makes sure it is behind the FV of platoon A. Once done, a merge request will be sent out by the OPCA through the iCLCM message, thus triggering the second phase.

Simultaneous Pair-Up: During this phase all vehicles from platoon B (e.g., b_j,) pair up with vehicles in platoon A (e.g., a_{i-1}). Each vehicle in platoon B targets the closest vehicle in front in platoon A and pairs up with it, and starts to open a gap to prepare the merge. The target vehicle, a_{i-1}, is the vehicle that will later merge in front of vehicle b_j in platoon B. This is a simultaneous process that all vehicles from platoon B perform at the same time. For vehicles in platoon B, the target in platoon A is called a forward pair (FWD pair), while the vehicle itself is called a backward pair (BWD pair) of its target. The FWD pair and BWD pair are denoted by the *FwdID* and *BwdID* fields within the iCLCM message.

Sequential Pair-Up: Consequently, as the vehicles in platoon B have simultaneously paired up with platoon A, the vehicles in platoon A start to pair up with the vehicles in platoon B in a sequential manner. Starting from the FV of platoon A, the vehicle pairs up with its closest vehicle in platoon B (which is also its BWD pair's predecessor at platoon B) and starts to make gaps.

During this phase, the BWD pair of the FV checks the gap between itself and its predecessor in platoon B. Once the gap is ready, a safe-to-merge (*STOM*) message will be sent out through the iCLCM message to its FWD pair (i.e., the FV), thus triggering the next phase.

FV Handover and Merge: A 0/1 flag is contained in the iCLCM message that denotes whether a vehicle is an FV or not. When the FV in platoon A receives a STOM, it switches its FV status from 1 to 0 and starts to merge. Meanwhile, its successor becomes a new FV by switching its FV status from 0 to 1, thus starting a new sequential pair-up as described above. Notice that the new FV does not need to wait for its predecessor to finish the merge, and can start sequential pair-up directly when the FV status is granted.

When vehicles from platoon A merge with vehicles in platoon B, a new platoon is formed, and normal platooning mode is active with necessary information exchanges.

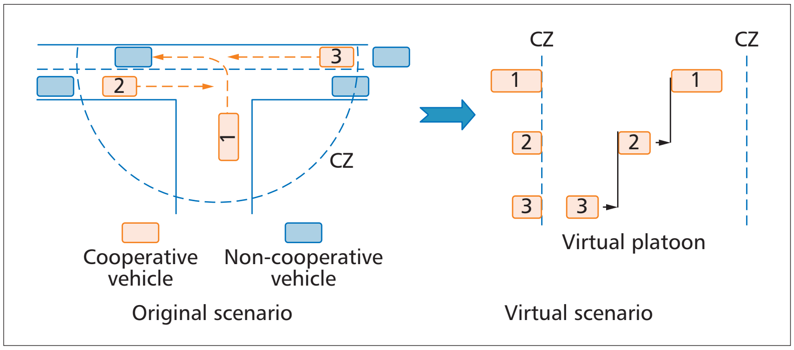

Figure 3. Scenario illustration: cooperative intersection and virtual platoon concepts.

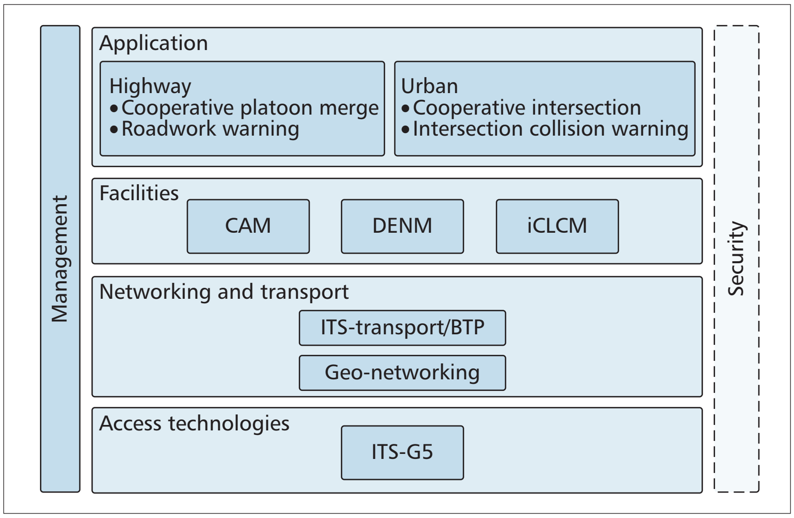

Figure 4. ITS station architecture.

It is acknowledged that the interaction protocol described here will be used during the challenge, while there are other interaction protocols developed such as that in [12].

Interaction Protocol for Cooperative Intersection

The interaction protocol for the cooperative intersection is based on the concept of virtual platoons [13]. Once vehicles enter the competition zone, vehicle information will be communicated and a virtual platoon will be formed. The procedure can be divided into two levels: a supervisory level and an execution level. The supervisory level manages the information of the vehicles in the virtual platoons that are approaching the intersection. The execution level is responsible for creating the virtual gaps between the vehicles in the virtual platoon by transforming the two-dimensional intersection into a one-dimensional virtual platoon, as shown in Fig. 3. Once the gaps are created, vehicles will continue driving in a cooperative adaptive cruise control fashion. To determine the order of the vehicles in the virtual platoon, each vehicle is assigned an index according to their entrance into the competition zone, the priority of the lane in which they are driving, and the intention of the vehicle. The information is contained in the iCLCM and is broadcast within the competition zone.

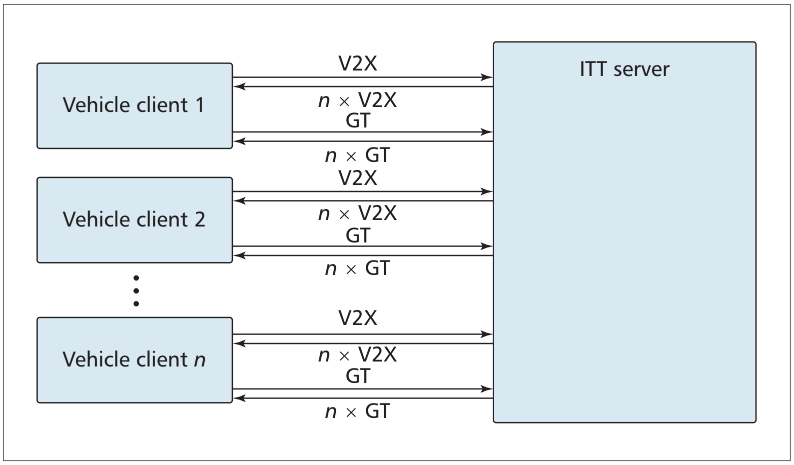

Figure 5. Interactive Test Tool architecture.

Interactive Test Tool

To facilitate the preparation of the challenge, the project provides tools and infrastructure to build and test cooperative systems. To perform remote over-the-Internet interoperability testing we have introduced the Interactive Test Tool (ITT) [14]. Figure 5 shows the architecture of the ITT. Vehicles, either realistic or simulated, access the ITT server for coordinating with each other to perform the scenario. As shown by the figure, for each of the vehicles, there are two types of information exchanged with the server, the V2X information and the ground truth (GT) information. V2X information is the normal information (CAM, DENM, and iCLCM) that will be broadcasted by the ITS-S when driving on the road, while the GT information represents the world model of the scenario. The ITT server is responsible for broadcasting ground truth (GT) to all vehicles and also redistributing V2X information to related vehicles.

The ITT facilitates the distributed development of cooperative systems in a mixed virtual and reality way, without revealing the internal algorithms of any of the teams. The tool enables testing of the entire system, including both the vehicle control system and communication stack. Through the ITT, the teams can test the interaction protocol for the cooperative platoon merge and cooperative intersection scenarios.

Requirements

To participate in GCDC2016, a number of requirements are established that concern both drivers and their vehicles. The requirements reflect the basic setting to be fulfilled when the teams develop their competition vehicles. The level of detail in the requirements does not constrain the design but rather inspires innovative solutions and allows an implementation space that is large but safe and interoperable. As for performance, a set of judging criteria is defined with consideration of both autonomy and cooperative aspects. They will be used by a group of experts for evaluating and grading the performance of different teams on both their individual and cooperative performance.

Driver Requirements

The human driver within the vehicle needs to fulfill a number of formal requirements, for example, having a valid driving license, having valid insurance according to the contract, and being aware of the safety and competition rules and instructions provided by the organizers.

Vehicle Automation Requirements

SAE standardized and published the taxonomy and definitions for vehicle automated driving systems in SAE J3016.[5] The six levels of automation from SAE are listed below.

- **Level 0:** No automation: the human driver performs all aspects of the driving task.
- **Level 1:** Driver assistance: one driver assistance system is active, either automated lateral or longitudinal control, while the human driver must monitor driving environment and perform fallback driving tasks.
- **Level 2:** Partial automation: one or more driver assistance system(s) of both automated lateral and longitudinal control, while the human driver must monitor the environment all the time and perform fallback driving tasks.
- **Level 3:** Conditional automation: the vehicle drives automatically but may require that the driver take over to perform fallback driving tasks.
- **Level 4:** High automation: the vehicle drives automatically even when the human driver fails to respond to a request from the vehicle to intervene.
- **Level 5:** Full automation: the vehicle drives automatically under all roadway and environmental conditions.

Vehicles with at least level 1 are allowed in GCDC2016, where the driver may be in control of lateral movements. The vehicles must have the ability to start and stop without the intervention of the driver. Furthermore, it is required that level 2 vehicles must have the ability to drive in level 1 mode, that is, with only longitudinal control in function.

The allowed vehicle types in GCDC2016 include personal cars, trucks, and vans as well as experimental vehicles. Autonomous vehicles (levels 4 and 5) are not eligible for participation in GCDC2016 unless they are equipped with V2V communication and follow the cooperative procedure. Besides the level 1 degree of automation, a number of general vehicle requirements are defined to maintain safety during the event, for example, minimum and maximum acceleration in both lateral and longitudinal direction for both automated driving and manual driving, vehicle communication devices, front/rear lights, and a physical emergency button for switching back to manual driving. The teams will be well informed on the safety procedure to make sure the challenge is performed in a safe way.

Accurate positioning, both absolute and relative, is an important feature for automated driving. The positioning accuracy of the vehicles is defined as the mean squared horizontal position error, DRMS. The requirement is that the position accuracy should be 2DRMS < 1 m. This corresponds to a probability of 95 percent for the values to fall into the DRMS circle. The accuracy of the proximity sensors measuring the distance to neighboring vehicles is also set to 2DRMS < 1 m. All vehicles shall have sensors for detecting the velocity, acceleration, and deceleration with a certain accuracy and with a certain update frequency:

[5] www.sae.org/autodrive

- Velocity accuracy ≤ 0.5 m/s
- Acceleration accuracy ≤ 0.2 m/s^2
- Deceleration accuracy ≤ 0.2 m/s^2
- Vehicle motion data update frequency 25 Hz.

Communication and Interaction Requirements

For cooperative driving, communication and interaction are the critical components in the vehicles' functional design [15]. In GCDC2016, this is based on C-ITS standards with certain modifications. All participating teams are required to follow the C-ITS standards for implementing communication devices. In addition, the ITS-S need to successfully interpret the iCLCM message set in order to perform the interaction protocol described previously. Specifically, a 200 m communication range and less than 100 ms communication delay needs to be guaranteed. Meanwhile, periodical message frequencies are specified between 1 and 25 Hz.

Besides the technical requirements are the ethical requirements, meaning that no cheating is tolerated such as sending fake information on purpose. This is guaranteed by a comprehensive framework to ensure a transparent and fair competition. Both the organization and individual teams will log all V2V communication messages during the challenge. This will be used to verify the information and allow the organizers to supervise the message contents and judge fairly.

The requirements were tested during a five-day safety workshop at the proving grounds of IDIADA in Spain, 29 March–2 April 2016. All participating vehicles successfully performed the safety tests and are thus fulfilling the safety requirements. A final check will be performed one week before the competition at the challenge site.

Conclusion

GCDC2016 is a unique event for worldwide researchers to showcase their recent developments on cooperative and automated vehicles based on the newly finalized C-ITS standards. In this article, we discuss the motivation of such a challenge based on the context of intensive work in C-ITS. Two challenge scenarios and one demonstration scenario, originating from the current ITS deployment, are presented. C-ITS communication architecture, which is the technology on which GCDC is based, is discussed, along with the new message set introduced to facilitate vehicle interaction. Interaction protocols, which form the core of vehicle cooperation, are presented in detail. A general introduction to requirements for participating in the GCDC is also given.

One important research topic, communication methods through cellular networks such as 4G-LTE, as well as the forthcoming 5G, is investigated within the project. While GCDC2016 focuses on ITS-G5 specified in C-ITS, integration with other types of communications forms is one of the most interesting areas for future work. In addition, interaction between vehicles in different traffic situations for both those investigated in the competition and other complicated traffic scenarios form another important area and calls for significant research.

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