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Cooperative Automated Maneuvering at the 2016 Grand Cooperative Driving Challenge

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Abstract—**Cooperative adaptive cruise control and platooning are well-known applications in the field of cooperative automated driving. However, extension toward maneuvering is desired to accommodate common highway maneuvers, such as merging, and to enable urban applications. To this end, a layered control architecture is adopted. In this architecture, the tactical layer hosts the interaction protocols, describing the wireless information exchange to initiate the vehicle maneuvers, supported by a novel wireless message set, whereas the operational layer involves the vehicle controllers to realize the desired maneuvers. This hierarchical approach was the basis for the Grand Cooperative Driving Challenge (GCDC), which was held in May 2016 in The Netherlands. The GCDC provided the opportunity for participating teams to cooperatively execute a highway lane-reduction scenario and an urban intersection-crossing scenario. The GCDC was set up as a competition and, hence, also involving assessment of the teams' individual performance in a cooperative setting. As a result, the hierarchical architecture proved to be a viable approach, whereas the GCDC appeared to be an effective instrument to advance the field of cooperative automated driving.**

Index Terms—**Cooperative driving, interaction protocol, controller design, vehicle platoons, wireless communications.**

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I. INTRODUCTION

COOPERATIVE driving is based on wireless communications between vehicles and between vehicles and roadside infrastructure, thereby providing the possibility to exchange information beyond the line-of-sight of individual vehicles, and to obtain information that cannot be retrieved via on-board sensors [1]. This, in turn, paves the way to create self-organizing behavior within and between groups of vehicles, aiming for increased traffic flow and traffic safety, while decreasing fuel consumption and emissions, in particular when combined with automation of the individual vehicle motion. Because of this potential, cooperative driving currently receives ample attention on a global scale [2]. Focussing on combined cooperative and automated driving, well-known applications in this field are truck platooning [3], [4] and cooperative adaptive cruise control (CACC) [5], both of which are aiming for short-distance vehicle following at, e.g., 0.3 s time gap, employing longitudinal vehicle automation to guarantee optimal and safe operation of the vehicles.

Platooning and CACC have been a focus for control-related research for many years, see, e.g., [6] and the literature references contained therein. Current research focusses on communication topologies [7], and on (the time-varying nature of) communication delays [8], in the scope of which [9] presents a stochastic approach, whereas [10] adopts recent results from the field of event-triggered control. In addition, traffic-level analysis of CACC is performed in, e.g., [11], evaluating the disturbance propagation properties of CACC in terms of traffic throughput and congestion.

While research into cooperative vehicle following is ongoing, it is to be expected that at some point, this will be extended towards cooperative maneuvering, i.e., also taking lateral vehicle motion into account. This expectation is based on two reasons. First, a platoon or vehicle string needs to allow for cut-in or cut-through maneuvers of other (cooperative and non-cooperative) vehicles. Second, more formations or traffic situations exist than only strings of vehicles, in particular for non-highway driving. This leads to new applications in the field of cooperative automated driving, which may jointly be referred to as cooperative automated maneuvering. This paper focusses on two such applications, being cooperative merging and cooperative intersection crossing.

Regarding cooperative merging, two branches can be identified in the current research, being individual vehicles either

merging to a highway from an on-ramp or merging into a platoon along the highway. As a representative example of on-ramp merging, [12] defines vehicle slots that can be occupied by vehicles. The underlying algorithm that manages the interaction between vehicles is based on the allocation of these slots. Another approach is proposed in [13] and [14], which involves a geometric characterization of the highway lanes and the merging zones, and aims to coordinate the time at which vehicles enter the merging zone. Regarding merging along the highway, [15] focusses on the design of trajectories needed for a vehicle to merge into a platoon; An algorithm to determine the merging location and the role of each vehicle is also presented. Finally, in [16], the concept of virtual platooning is introduced, having the advantage that the proposed merging approach is applicable for various merging scenarios, such as on-ramp and on-the-highway merging; Here, the virtual platooning concept is employed to design a speed trajectory for the merging vehicle to align it with the gap, while taking into account velocity variations of the vehicles in the target lane.

Intersection-control research also offers two branches, i.e., cooperative resource reservation and trajectory planning. In cooperative resource reservation, the intersection space is separated into time-space tiles that are assigned to vehicles and scheduled to achieve a safe crossing. The reservations can be managed by a centralized unit, as in [17] and [18], or in a distributed manner, as in [19] and [20]. The trajectory-planning approaches focus on the movement of vehicles relative to a fixed point in the intersection (which resembles the on-ramp merging solutions) to achieve a safe crossing of vehicles. In the centralized solution in [21], the information of the vehicles is used to predict their trajectories through the intersection, upon which these predictions are used to calculate the optimal crossing sequence. As a more practical approach, the distributed solution in [22] establishes the crossing sequence based on road priorities.

The main contribution of this paper is to present an approach to cooperative maneuvering, in particular merging of two strings of vehicles on a highway and intersection crossing, which is based on extending the notion of platooning. Since cooperative maneuvering not only involves control but also decision making, wireless communication-based interaction protocols are presented and placed in a hierarchical automation architecture. This hierarchical approach was the basis for the Grand Cooperative Driving Challenge (GCDC), which was held in May 2016 in The Netherlands. As a second objective, this paper aims to present the GCDC in more detail.

The GCDC 2016 was organized as part of the European Seventh Framework Programme project i-GAME [23] and was actually a follow-up of the first GCDC in 2011 [24], [25], which exclusively focused on CACC. The main objective of the GCDC 2016 was to provide a basis for development of cooperative automated driving applications in an international context. To this end, a multi-brand approach was adopted, where vehicles from different manufacturers can cooperate based on a minimum set of common rules such as safety regulations and communication protocols [26]. In particular, the GCDC aimed to involve multiple parties

TABLE I
GCDC 2016 PARTICIPATING TEAMS

Team	Institution
AnnieWAY	Karlsruhe Institute of Technology, Karlsruhe, Germany
A-Team	Eindhoven University of Technology / Fontys University of Applied Sciences, Eindhoven, The Netherlands
Chalmers Car	Chalmers University of Technology, Gothenburg, Sweden
Chalmers Truck	Chalmers University of Technology, Gothenburg, Sweden
Drivertive	University of Alcalá, Alcalá de Henares, Spain
Halmstad	Halmstad University, Halmstad, Sweden
Heudiasyc	University of Technology of Compiègne, Compiègne, France
KTH Experimental Car	KTH Royal Institute of Technology, Stockholm, Sweden
KTH Truck	KTH Royal Institute of Technology, Stockholm, Sweden
Latvia	University of Latvia, Riga, Latvia

from academia and industry to jointly develop and implement cooperative driving applications, while exploring the required functionality regarding vehicle automation and interaction protocols. In general, an important aspect in this development is the ITS-G5 wireless communication standard for mobile applications [27], [28]. The GCDC addressed the ITS-G5 communication standard by providing an environment to test this standard in practice, especially with respect to the suitability of the standardized message content to perform advanced maneuvers. To this end, a competition was set up consisting of two traffic scenarios, being highway merging of two lanes and an intersection crossing, and teams were invited to participate; See Table I for an overview of the participating teams. In the close-to-reality context of the GCDC, these teams were given the freedom to implement their own control solutions, as will also be the case in real-life multi-brand cooperative maneuvering, provided that the common interaction protocol is supported.

The outline of this paper is as follows. Section II presents the aforementioned GCDC traffic scenarios in more detail. Next, Section III introduces a functional architecture for cooperative automated maneuvering, providing the context for the interaction protocols that are required to cooperatively execute these scenarios, which are introduced thereafter. In addition, specific control solutions as developed by the GCDC organization are presented. Subsequently, Section IV focusses on the requirements imposed on the ITS-G5 communication system and presents a new message set to support the interaction protocol, while also elaborating on a tool to test the conformity to the defined interaction protocol. Section V and Section VI are dedicated to the competition aspect of the GCDC, explaining the performance criteria and the main safety aspects, respectively. Finally, Section VII reflects on the GCDC by presenting the lessons learned and the main conclusions.
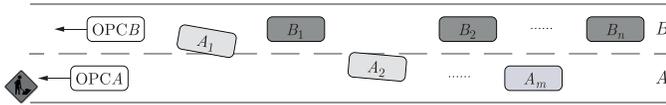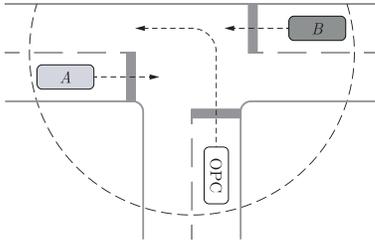
Fig. 1.   Highway lane-reduction scenario.

Fig. 2.   Urban intersection-crossing scenario.

Fig. 3.   Functional architecture for cooperative automated maneuvering.

II. COMPETITION SCENARIOS

To show that cooperative automated maneuvering can be deployed in various environments, two scenarios were selected by the GCDC organization, covering both a highway and an urban environment.

The highway scenario, as illustrated in Fig. 1, involves a lane reduction from two lanes to one lane due to, e.g., roadworks, causing the vehicles on the left lane (labeled as A_i, $i = 1, 2, \ldots, m$) to merge with the vehicles on the right lane (labeled as B_j, $j = 1, 2, \ldots, n$). Consequently, the scenario execution involves maneuvers such as vehicle following, gap making, and changing lanes, while maintaining a safe distance throughout the entire merging procedure. As will be explained later, this scenario was executed multiple times in the GCDC. Hence, to ensure reproducibility of the scenario, organization pace cars (OPCs) at the head of the platoon on the left and the right lane were included in the scenario, in Fig. 1 denoted as OPCA and OPCB, respectively. These OPCs were responsible for adjusting the speed and relative distance of the two platoons. Also, some of the organizational commands, such as requests for a merge, were issued using these vehicles. The original speed limits were assumed to be 60 and 80 km/h for the right and left lanes, respectively, which was reduced to 40 km/h upon arrival to the construction site by means of a wireless message from the roadside. This speed reduction and synchronization was supported by the OPCs as well.

The urban scenario focuses on cooperative crossing of a T-intersection without traffic lights, in which the approaching vehicles should coordinate their longitudinal motion to avoid collisions in the first place, but also to avoid coming to a full stop, which would compromise throughput. Fig. 2 illustrates this intersection-crossing scenario. Here, the vehicles enter the crossing at the same moment, such that, without adaptation of their speed, a collision would occur. It is noted that this scenario also includes an OPC, as indicated in Fig. 2, for reasons of reproducibility.

Both scenarios involve an interaction protocol, defining the messages to be exchanged between the vehicles, to allow for coordinated execution of the scenarios, as further explained in the next section.
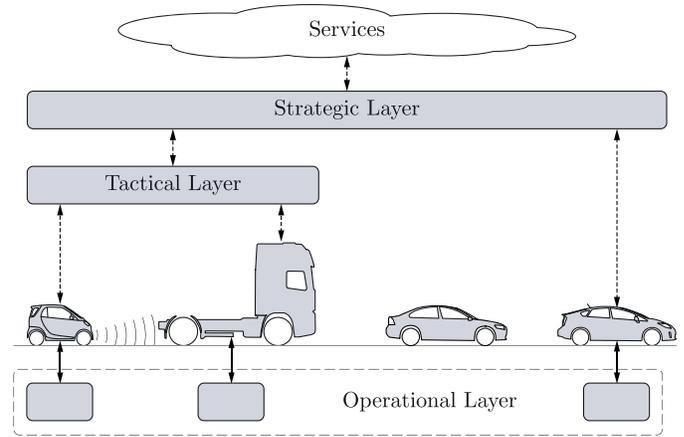
III. CONTROL SYSTEM DESIGN

A. Functional Automation System Architecture

Being able to automatically control vehicles, which are collaborating in a particular scenario, requires a common behavior enabled by a functional architecture and a corresponding interaction protocol. To this end, a layered architecture is proposed, inspired by [29], among others, to allow decentralized negotiation in the two scenarios. The proposed architecture, as depicted in Fig. 3, consists of three layers, explained below.

- The *Strategic Layer* is responsible for the high-level decision making regarding, e.g., routing, optimization of fuel consumption, travel times, and, in case of platooning, the scheduling of platoons based on vehicle compatibility, destination, and impact on highway traffic flow and infrastructure. To this end, the Strategic Layer may utilize cloud-based services.
- Driven by the Strategic Layer, the *Tactical Layer* coordinates cooperative maneuvers, such as platoon forming, merging, intersection crossing, and also speed synchronization between neighboring vehicles, to support lane changes in heavy traffic. As such, this layer runs the aforementioned interaction protocol. Depending on the type of application, the Tactical Layer can be implemented in a distributed or in a centralized manner.
- The *Operational Layer* involves the actual real-time vehicle control to execute the required maneuvers, amongst which platooning and merging.

It should be noted that in the context of the GCDC, it was not feasible to apply an architecture that supports formation-like controllers [30], [31] or even a more generic approach based on consensus seeking [32], since this would require all vehicles to implement exactly the same type of vehicle motion controller, whereas in the GCDC, the control approach could be freely chosen by each participant. Nevertheless, the presented architecture does assume all vehicles to be cooperative. In mixed traffic, i.e., consisting of both cooperative and non-cooperative vehicles, a degraded mode should automatically come into operation, with corresponding decreased functionality. This is, however, outside the scope of this research.
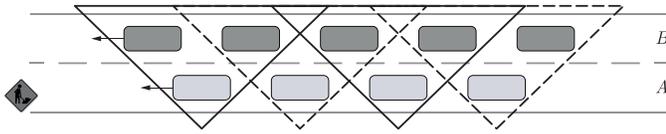
Fig. 4. Breakdown of a platoon merging into single-vehicle merging.

The remainder of this section introduces the interaction protocols, which were developed for both scenarios, and describes the underlying real-time controllers to realize the required maneuvers.

B. Interaction Protocols

1) Highway Lane-Reduction Scenario: To be able to realize a lane reduction as illustrated in Fig. 1, the entire scenario is first simplified by breaking down the two platoons into modules consisting of three vehicles, as shown in Fig. 4. These paired triplets are chosen from the two platoons and are going to interact for the sake of merging and gap making. Then, within each of these triplets, a similar interaction protocol is implemented, see [33]. The decision on who is going to be in each triplet, is mainly based on the relative position of the vehicles. That is, a vehicle most probably prefers to merge in front of a car which is the closest, with some exceptions such as merging in between two trucks. This strategy enables all vehicles to decide for their appropriate pairs locally, without a need for a supervisor (e.g., a platoon leader) to do the assignment. In the following, a summary of the protocol, presented in [33], is given.

Let the merging platoon be denoted by A and its members are labeled as A_1 to A_m. Similarly, the gap making platoon, driving on the right lane, and its members are denoted by B and B_1 to B_n, respectively. The first vehicle on each lane is the OPC, which is meant for reproducibly tuning the initial relative positions of the two platoons, see Fig. 5.

Some major challenges exist, specific to platoon merging, when compared to single car merging, being:

1) Simultaneous gap making/merging of the entire platoon results in huge deceleration at the tail of platoon B which is not desirable.
2) Serial gap making/merging, i.e., one vehicle at a time, is not time-efficient.
3) Due to simultaneous merging requests, several vehicles might respond with a safe-to-merge message. This can be a source of confusion for the merging cars.

Hence, to be able to address these challenges, the following multi-stage interaction protocol was developed for the GCDC challenge. This protocol facilitates the implementation of a combination of the serial and simultaneous merging strategies for platoon merging:

   i. **Pace Making**: It is assumed that the relative position of the two platoons is at an approximately desired value before start of the competition, being in an overlapping situation. Due to the speed difference between the two lanes, this situation will not last much unless that the speeds of both platoons are synchronized. Therefore, at this stage, an intelligent roadside unit (RSU) informs all vehicles in platoon A and B of the upcoming work site at
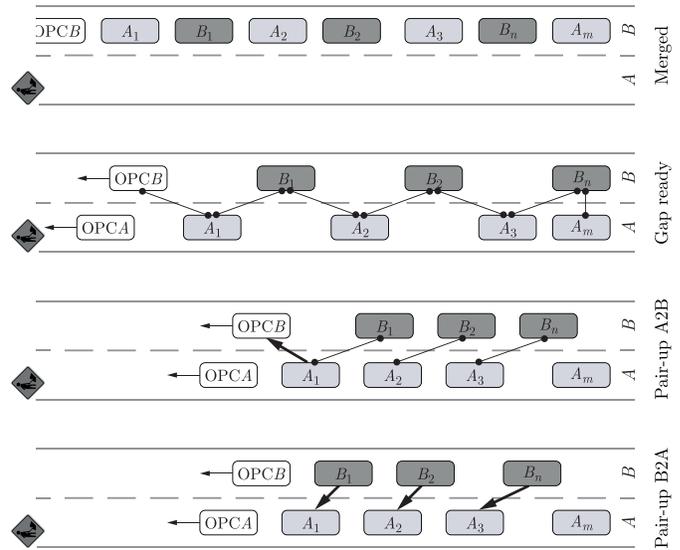

Fig. 5. Stages of the lane-reduction scenario.

the same time, i.e., a broadcasted message. Afterwards, platoon A and B both decrease their speed to an advised speed, being 40 km/h, as well as tune their relative positions. This tuning is done such that the relative positions are at a desirable condition, e.g., such that OPCB is in front of A_1, see Fig. 5.

Pace making thus serves the GCDC-specific purpose of creating adequate initial conditions for the challenge. More importantly, the pace making phase also guarantees that there are no large speed differences between the adjacent strings of vehicles, which is desired for the Simultaneous Pair-up phase as described next.

   ii. **Simultaneous Pair-up (B2A)**: When the relative position and velocity of the two platoons are aligned, OPCA sends a merge request to platoon B. Upon arrival of this merge request, platoon B starts to make gaps by *simultaneous pair-up* with A, see the black arrows in Fig. 5 (Pair-up B2A). This stage is meant to provide part of the gap needed for merging of platoon A into platoon B. Since the required gaps between the vehicles in platoon B with respect to those in platoon A are, in fact, created by changing the relative position of both platoons, this stage of pair-up is not likely to result in large decelerations of the vehicles in platoon B. Therefore, this pair-up can be performed by all vehicles in platoon B simultaneously. Specifically, each vehicle B_i ($i = 1, 2, \ldots, n$) in platoon B takes the front car on the left lane with shortest relative distance (from its front bumper to the target's rear bumper) as the pairing partner. This target should not be further ahead than the front car on the main lane. This object is denoted as the forward most-important-object (MIO) on the left lane. Note that, by definition, this MIO is unique. Therefore, there is no possibility that multiple pairs are selected at the same time. The IDs of the paired vehicles are communicated through the vehicle-to-vehicle (V2V) communication. If the pair proposal is accepted by the pair candidate A_j in platoon A, B_i makes a gap with

respect to its pairing partner, A_j. This results in a large-enough gap between the two paired vehicles.

iii. **Sequential Pair-up (A2B)**: After platoon B is paired-up with platoon A, the latter starts to pair-up with platoon B, see Fig. 5 (Pair-up A2B). At this stage, the rest of the gap required for a merging action, is created. This gap-making, however, potentially leads to accumulation of the subsequent gaps towards the tail of both platoons A and B, which can readily be seen from the final situation depicted in Fig. 5 (Gap ready). In other words, parallel gap making in this stage can result in huge deceleration at platoon tails. Therefore, this stage is executed by means of a *sequential pair-up*. The decision on when the pairing should be initiated is based on certain criteria, e.g., a fixed time after a merge request is sent by OPCA. The choice of a forward pair for A_j, is done such that forward and backward pairing with two non-consecutive vehicles is avoided. That is, each vehicle in platoon A chooses the direct predecessor of its backward partner as its forward partner, e.g., if B_i is the backward partner of A_j, then B_{i-1} becomes the forward partner of A_j. To enable A_j to decide about its forward partner, B_i needs to send the ID of its direct predecessor through a wireless message. In case that no backward pair exists, the forward pair is selected to be the forward MIO on the right lane. This pairing stage is done only once and is not updated during the scenario execution. Also, both the pairing of platoon A to B as well as the gap-making are done in a sequential manner. That is, this pairing is done one vehicle at a time, starting from the lead vehicle, A_1. The rest of the vehicles in platoon A should wait until the pairing/gap making of the vehicle in front of them is finished. This is indicated by broadcasting a "merging" status through the wireless link. Upon this, A_1 hands over its role as the platoon lead vehicle to A_2, i.e., the "lead flag" of A_1 shifts to zero. Then, the car behind it becomes the new platoon lead vehicle. As soon as A_j merges, all the pair flags of A_j and its partners shift to zero, opening the room for its pairing partners to re-pair with other relevant vehicles of platoon A.

iv. **Gap-ready and STOM generation**: When the gap is ready, vehicle B_i sends out a safe-to-merge (STOM) message, targeted at its paired partner in platoon A, i.e., A_j. As soon as A_j receives the STOM message from its paired partner, it will go to merging status (indicated by a merging flag). This opens the room for the next vehicle A_{j+1} in platoon A to start pairing and making a gap while A_j is merging. As it can be deduced from the procedure, this stage has also a sequential manner, i.e., no vehicle can start merging before the car in front of it sets a merging flag.

Remark 1: Note that in design of the above interaction protocol, different criteria were considered. To name some, driver acceptance, comfort, safety, and traffic efficiency can be mentioned. Therefore, though quite important, the traffic flow optimization was not the ultimate goal.

2) Intersection-Crossing Scenario: To be able to execute the intersection crossing scenario as illustrated in Fig. 2, a so-called Competition Zone (CZ) is defined, being a circular region with its center coinciding with the center of the T-intersection, in which vehicles are allowed to react to each other. When all vehicles involved in the scenario enter the CZ at the same time, which is ensured by a scenario start message issued by the RSU, the so-called target vehicle assignment (TVA) subsystem is activated. This subsystem checks the lane, intention and priority of each vehicle to form a *virtual platoon*, being a platoon of vehicles that are actually driving on different lanes. To form such a virtual platoon, each vehicle calculates a virtual inter-vehicle distance between the assigned target vehicle and itself. Then, this distance is fed to the vehicle-following controller (i.e., CACC) to realize a desired virtual inter-vehicle distance. The virtual inter-vehicle distance is defined such that, if it equals its desired value, it ensures that vehicles (with crossing trajectories at the intersection) travel through the intersection at a safe distance. It is noted that the speed difference between the assigned target vehicle and the follower vehicle at the moment of assignment should not be too large, thereby preventing high decelerations or accelerations of the follower; This requirement is similar to the requirement for the simultaneous pair-up in the merging scenario regarding limited speed difference between the adjacent strings of vehicles.

To avoid the trivial situation in which the vehicle from the crossroad (OPC in Fig. 2) is positioned in the virtual platoon after the vehicles A and B on the main road, the crossing vehicle is actually an OPC which has priority, meaning that it is assigned as the platoon leader by the TVA. The TVA of vehicle A checks the information of both the OPC and vehicle B, and determines that the trajectories of vehicle A and B do not cross, but that the trajectories of vehicle A and the OPC do cross; Hence, the OPC is assigned as the target vehicle of vehicle A in the virtual platoon. In the same fashion, the TVA of vehicle B assigns the OPC as its target vehicle since their trajectories cross, and ignores vehicle A since they have non-crossing trajectories.

It is noted that the virtual platoon forming procedure can be generalized to other vehicle trajectories, as well as to other road layouts [34].

C. Controller Design Approach

1) Highway Lane-Reduction Scenario: Here, an example of a possible control approach to realize a lane-reduction scenario is given. This method was implemented to the same vehicles as were used as OPC, developed by the organizing consortium of the GCDC event. It should be noted that although the details of this method were accessible to all participants, it was not enforced to be implemented by the teams, thus illustrating the design freedom as mentioned in Section I.

Consider a vehicle in a platoon of m vehicles, see Fig. 1, being controlled by a one-vehicle look-ahead cooperative adaptive cruise control (CACC), as described in [35], to control the distance toward the preceding vehicle. Also, an additional gap-making controller, as described in [36], is used to make the gap that is needed to complete a merging scenario.
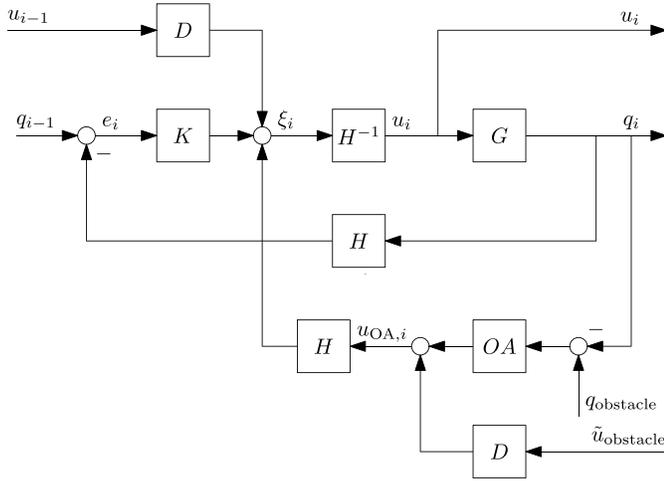
Fig. 6. Block diagram of a controlled vehicle in a platoon with active CACC and OA controller agents.

TABLE II
VEHICLE AND CONTROLLER PARAMETERS

Symbol	Value	Name
τ	0.1 s	Engine time constant
θ	0.02 s	Communication time delay
h	0.6 s	Time gap
r	2.5 m	Stand-still inter-vehicle distance
L	2.7 m	Length of the vehicle

In other words, this controller, referred to as the obstacle avoidance (OA) controller (different from a collision avoidance controller), 'sees' the merging vehicle as an obstacle and tries to avoid it by making a gap. In the controller implemented in the organization vehicles, the control effort from these two controllers are added. The resulting closed-loop dynamics for vehicle i in the platoon, with a third-order linear dynamic vehicle model, subject to the CACC as well as the OA controller, is presented in the block diagram shown in Fig. 6. There, q_i, v_i, and u_i are the position, velocity, and longitudinal control input, and $e_i(t) = d_i(t) - d_{r,i}(t)$ is the distance error, where $d_i = q_{i-1} - q_i$ is the distance between vehicle i and $i - 1$ (assuming zero vehicle length without loss of generality), and $d_{r,i} = r + hv_i$ is the (velocity-dependent) desired distance. Also, r and h denote the standstill distance and the time gap between two vehicles. Here, u_i represents the entire external input (i.e., the desired acceleration) implemented to vehicle i, which is equal to $u_i = u_{\text{CACC},i} + u_{\text{OA},i}$, where $u_{\text{CACC},i}$ and $u_{\text{OA},i}$ are the CACC and OA control efforts, respectively. Moreover, in Fig. 6,

$$G(s) = \frac{q_i(s)}{u_i(s)} = \frac{1}{s^2(\tau s + 1)}$$
$$H(s) = hs + 1$$
$$D(s) = e^{-\theta s} \tag{1}$$

with $s \in \mathbb{C}$, whereas $K(s)$ is the vehicle following controller (CACC). Here, $q_i(s)$, and $u_i(s)$ are the Laplace transforms of $q_i(t)$ and $u_i(t)$, respectively, θ is the time delay induced by the wireless communication network, and τ is the vehicle's drive-line time constant. Also, q_{obstacle} is the obstacle's position, e.g., the merging car, $\tilde{u}_{\text{obstacle}}$ is the deceleration of the obstacle, i.e., equal to u_{obstacle} if $u_{\text{obstacle}} < 0$ and equal to 0 if $u_{\text{obstacle}} \geq 0$, and OA is the nonlinear function representing the OA controller [36]. The parameters of the dynamical model (1) are given in Table II.

In summary, the merging approach is based on feedback control by means of 1) CACC with the directly preceding vehicle in the same lane as a target and 2) OA with respect to the paired vehicle in the adjacent lane. This approach for gap making and gap alignment has the advantage of being robust against velocity disturbances caused by other traffic, either or not engaged in the merging procedure.

2) Intersection-Crossing Scenario: The safe crossing of the intersection is achieved using the virtual platooning concept, with the same motivation as in the merging scenario, i.e., robustness against velocity disturbances caused by other traffic. The formation of the virtual platoon is the main challenge and depends on coordinate transformations to translate the two-dimensional intersection problem into a one-dimensional platooning problem. The implementation of virtual platooning employs the aforementioned coordinate transformations and the different vehicle control modes such as: Cruise Control (CC), Cooperative Adaptive Cruise Control (CACC), and Virtual CACC (VCACC). The switching between modes is implemented by a supervisory controller, which monitors the state of a vehicle in the virtual platoon. The remainder of this section outlines the virtual platoon forming, whereas the actual virtual platooning controller is described in [6].

Every vehicle i that enters the CZ of the intersection will follow a path $\mathcal{C}_{k,\eta}^i$ with an associated curvilinear path coordinate s_i, where k is the enumerated input lane and η is the vehicle intention (namely, straight ($\eta = 1$), left ($\eta = 2$), or right ($\eta = 3$)); See Fig. 7 for a path example, where $k \in \{1, 2, 3\}$ and a_k denotes the entry point of lane k.

Consider the target vehicle V_n, which drives along a path $\mathcal{C}_{k,\eta}^n$, that is followed by the host vehicle V_m, which drives along its path $\mathcal{C}_{k,\eta}^m$. Note that $\mathcal{C}_{k,\eta}^m$ and $\mathcal{C}_{k,\eta}^n$ have associated curvilinear path coordinates s_m and s_n, respectively. Let $\mathcal{C}_{k,\eta}^m$ and $\mathcal{C}_{k,\eta}^n$ be two trajectories that cross at the collision point $b_{m,n}$, as shown in Fig. 7. Then, $S_m = \int_{a_m}^{b_{m,n}} \mathrm{d}\sigma_m$, where $\mathrm{d}\sigma_m$ is a path coordinate differential measure of the path $\mathcal{C}_{k_m,\eta_m}$, is the distance to collision for the host vehicle V_m. Similarly, $S_n = \int_{a_n}^{b_{m,n}} \mathrm{d}\sigma_n$, where $\mathrm{d}\sigma_n$ is a path coordinate differential measure of $\mathcal{C}_{k_n,\eta_n}$, is the distance to collision for the target vehicle V_n. Then we can define the virtual inter-vehicle distance δ_m between the host vehicle V_m (with length L) and the target vehicle V_n as

$$\delta_m = s_n^* - s_m - L \tag{2}$$

where

$$s_n^* = \frac{S_m}{S_n} s_n \tag{3}$$

is the scaled path coordinate of V_n. This scaling procedure allows the comparison of the path coordinates of vehicles travelling on paths with different distances to collision. Note that the scaling also applies to the velocity and acceleration
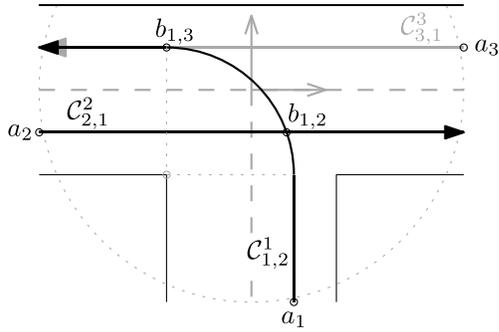
Fig. 7.   T-intersection with the possible paths.

of vehicle V_n, such that $v_n^* = \dot{s}_n^*$, and $a_n^* = \ddot{s}_n^*$, respectively. The virtual inter-vehicle distance in (2) is used to realize a virtual desired inter-vehicle distance $\delta_r = r + hv_n$, where r is the standstill distance, h is the time gap, and v_n is the host vehicle velocity. The values of the relevant parameters are shown in Table II. The CACC used to realize this virtual inter-vehicle distance is presented in [6].

It is noted that aiming for a virtual inter-vehicle distance is only necessary until the vehicles have crossed the collision point. Therefore, the VCACC is deactivated for $s_m > S_m$. After the VCACC is deactivated, the vehicle switches to CACC if a vehicle is detected by its radar, and to CC if it has a free road in front. To combine the different control modes, a control reconfiguration with mixing is performed. Consider to this end a vehicle i with desired acceleration u_i as input, and that each control mode produces an individual input, namely $u_{1,i}$, $u_{2,i}$, and $u_{3,i}$ for the CC, CACC, and VCACC control modes, respectively. Then, the input u_i of vehicle i is the convex combination of the control efforts of the individual control modes, given by

$$u_i = \sum_{k=1}^{3} \beta_k u_{k,i} \qquad (4)$$

where the mixing signals $\beta_k > 0, \forall\ k\ \in\ \{1, 2, 3\}$, and $\sum_{k=1}^{3} \beta_k = 1$. A detailed explanation of the formation and execution of the virtual platoon is given in [34].

Having outlined the control approach for both traffic scenarios, while also indicating the interaction protocols and the associated wireless information exchange, the next section will provide more insight into the wireless communication standard and, particularly, the required adaptations to support the interaction protocols for the selected traffic scenarios.

IV. WIRELESS COMMUNICATIONS

A. Specification of Communications

In ITS, the availability of a protocol stack as well as a reference implementation for it, are prerequisites. In i-GAME, a bottom-up approach is used for designing the communication architecture and message sets. This is done using the experience gained from the previous GCDC in 2011 [24], [25] as starting point, as well as ongoing C-ITS standardization efforts [37]–[39]. From the i-GAME project perspective, the

following high-level requirements for the wireless communication protocol stack are adopted:
- To maximize conformity to current standards;
- To support the GCDC interaction protocols;
- To be implementable by the participating teams considering computational resources.

For the lowest layers in the stack, it was decided to use ITS-G5 [40] as access technology, and ETSI GeoNetworking [41] for network and transport. Detailed information on the wireless communication architecture and basic specifications used for the GCDC, are available at D3.1 in [42]. In addition, supporting tools to test and validate the V2V communications were needed. For this, a low-cost reference communication unit was developed. With operating system-specific adjustments to support ITS-G5 configurations and setting up ITS-G5-capable radios and drivers. This platform was used to run an open-source ITS-G5 communication stack [43], supporting the messages sets as further explained below. This proved to be a flexible tool for setting up V2V communications and testing interactions. The interoperability of the GCDC reference communication unit was successfully tested during the *ETSI ITS Cooperative Mobility Services Event 4* [44].

B. iCLCM Message Set Description

The scenario execution is heavily based on V2V communication; Communication with infrastructure units is also used, but only for scenario management such as starting the scenario, interrupting the scenario for safety reasons, monitoring the progress, and data logging. Therefore, it was evaluated how existing standardized message sets could support the GCDC.

During the project execution, the European Telecommunications Standards Institute (ETSI) published European norms related to the Cooperative Awareness Message (CAM) [37] and the Decentralized Environmental Notification Message (DENM) [38]. CAM and DENM, in fact, constitute a particular message content, serving the purpose of (time-triggered) cooperative awareness messages and (event-triggered) notification messages, respectively. As such, these messages have an informative character. In the GCDC, however, and particularly in the highway lane-reduction scenario, an application-level handshaking mechanism is included to implement the pair-up procedures, which is not supported in either of the aforementioned message sets, nor in the so-called Basic Safety Message (BSM) as adopted in the United States [45]. Hence, it was concluded that additional information is needed to support the GCDC scenarios, resulting in a new message set, referred to as the i-GAME Cooperative Lane Change Message (iCLCM). Note that this approach has also been adopted in [46] for the same reasons. Where possible, the iCLCM is aligned with the available Common Data Dictionary (CDD) technical specification [39].

The iCLCM message set for performing the i-GAME scenarios is designed using the following procedure:
1) First, the main stages of the execution of the GCDC scenarios are identified, while constructing message flow diagrams;
2) From the message flows, the set of signals required by the in-vehicle control system are determined;

3) This is subsequently mapped on the information available from the CAM and DENM messages;
4) Finally, missing information is identified and mapped to a new message set, i.e., the iCLCM message set.

The design used for the iCLCM is comparable with the CAM message, i.e., a periodical single-hop broadcasted message. The iCLCM is composed of a header and multiple containers, which constitute the iCLCM payload. In particular, the iCLCM payload consists of the following containers:

- *High Frequency*, with additional dynamic information about the vehicle;
- *Low Frequency*, with information (static, non-temporal) that does not need to be updated at high frequency;
- *MIO* (Most Important Objects), containing information about the immediate neighbor vehicles;
- *Lane*, being the identification number of the lane on which the vehicle enters the Competition Zone;
- *Pair ID*, containing the station identification number of the pairing partner;
- *Merge*, being a container with all information needed to perform the actual merging;
- *Scenario*, with additional information needed for scenario execution.

Further details on the methods used for designing the iCLCM and the final solution created for the GCDC, are available at D3.2 in [42]. It should be noted that the iCLCM is not put forward as a candidate for standardization, since that would require a more thorough investigation of communication message sets for cooperative maneuvering scenarios in general. Nevertheless, the need for such a message set to implement this type of scenarios is apparent.

At the facility layer, we use non-standard frequencies of 1 up to 25 Hz for iCLCM (and also for CAM). Such a relatively high update rate is needed due to very strict safety measures, taking into account that the automation system of vehicles involved in the scenario are usually time-triggered, with asynchronous sampling time instances among the vehicles. Consequently, this update rate enables practical scenario execution without large vehicle gap openings or slow maneuvering, which would deviate from real-life vehicle behavior.

The CAM and DENM messages are defined in the Abstract Syntax Notation 1 (ASN.1) format. This notation describes the structure and contents of the messages. The data elements and frames available from the CDD can be used to construct the CAM and DENM messages. The iCLCM definition was also provided as ASN.1 file to the GCDC teams. Finally, Unaligned Packed Encoding Rules (UPER) as defined in Recommendation ITU-T X.691 [47] is used for the message encoding and decoding.

Multiple tools are developed to be used for the GCDC and during preparation activities for setting up communication, testing the V2V communication (conformance testing) and for interaction testing, one of which is described hereafter.

C. Interactive Test Tool

To facilitate the preparation of the challenge, the project provided tools and infrastructure to build and test cooperative
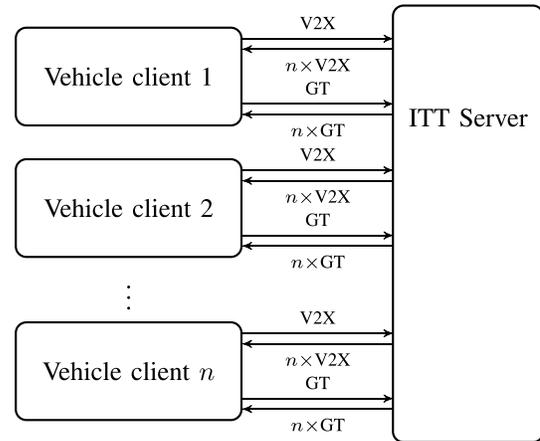

Fig. 8. Interactive Test Tool architecture.

systems. To perform remote over-the-Internet interoperability testing, the Interactive Test Tool (ITT) was introduced [48]. Fig. 8 shows the architecture of the ITT. Vehicles, either real or simulated, access the ITT server for coordinating with each other to perform the scenario. For each vehicle, there are two types of information exchanged with the server: the V2X information and the Ground Truth (GT) information. V2X information is the wireless information (CAM, DENM, and iCLCM) that will be broadcasted by the vehicles when driving on the road, while the GT information represents the world model of the scenario, i.e., the ground-truth position, velocity and acceleration of the participating vehicles. The ITT server is responsible for broadcasting GT information to all vehicles and also redistributing V2X information to related vehicles.

The ITT facilitates the distributed development of cooperative systems, where teams can test their implementations together 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 the communication stack. In the GCDC, the ITT allowed the teams to test their implementation of the interaction protocols for both scenarios.

V. Judging

A. Motivation and Background

The GCDC aimed to explore cooperative maneuvering scenarios through cooperation of the participating teams (see Table I). However, the additional element of competition was included to stimulate teams to perform at their best. This section describes the associated judging criteria as developed in the i-GAME project and presents the main judging results.

Judging criteria may be viewed to reflect *quality* requirements next to the *functional* requirements, as expressed by means of the scenarios and interaction protocols. The judging process deals with three dimensions of concerns:

1) multiple competition scenarios, as described in Section II,
2) multiple levels of vehicle automation, and
3) multiple judging categories.

Compared to the GCDC in 2011, the latter two concerns were novel for the GCDC in 2016.

Since basic cooperative platooning capabilities are a pre-requisite for participation, the automation level of the participating vehicles is required to be of SAE Level 1 [49], e.g., longitudinal control. Vehicles may, but need not, support higher levels of automation, such as additional lateral control. These different levels of automation gives rise to an additional challenge for judging. Note that teams having vehicles with a higher automation level were neither penalized nor favored.

Cooperation and safety are crucial for the competition, which is why multiple judging categories were defined. Next to technical performance, two non-technical categories were devised, being assistance and support (A&S) and human-machine interaction (HMI). Whereas the former focuses on how a team cooperates with other teams, the latter focuses on safety aspects from an HMI-perspective for cooperative and autonomous vehicles. From these three categories, technical performance received the highest weight in judging.

In the remainder of this section, judging individual performance in a cooperative setting is considered first, after which an overview of the judging criteria for the three judging categories is provided. Finally, the main judging results are presented.

B. Judging Individual Performance in a Cooperative Setting

Transparency of judging towards teams, and objectivity of judging is of utmost importance, obviously. The former was accomplished through involvement of the teams in the definition of the judging criteria, see D7.1 in [42], and the formalization of the technical criteria. The latter was accomplished through automated judging of technical criteria, which also enabled immediate feedback to teams of their performance after a heat, as well as immediate visibility of performance of the teams to the audience. Technical judging is based on data logged by three independent sources, i.e., the OPCs, the participants' vehicles, and the RSUs of the test site, see Fig. 9. Such data logged by a participant's vehicle could be viewed as a further extension of the data recorded by a so-called Event Data Recorder (EDR),[1] i.e., "*a device or function in a vehicle that records a vehicle's dynamic time-series data just prior to or during a crash, intended for retrieval after the crash*" [51]. In 2012, the U.S. DoT proposed a broader use of EDRs to help improve vehicle safety [52]. Extensions of EDRs for active safety have been proposed in [53]. Further extension of EDRs with communication data is considered crucial for future cooperative automated driving.

The two non-technical categories are inherently judging teams individually. For the technical category, two types of judging are defined per competition scenario, i.e., *individual* and *group* judging, which ensures that teams are not only judged based on individual performance but also on cooperative aspects. Examples of both types are described below.

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[1] According to [50], the National Highway Traffic Safety Administration (NHTSA) of the United States Department of Transportation (U.S. DoT) estimates that approximately 96% of the passenger cars of model year 2013 are already equipped with EDR capabilities.
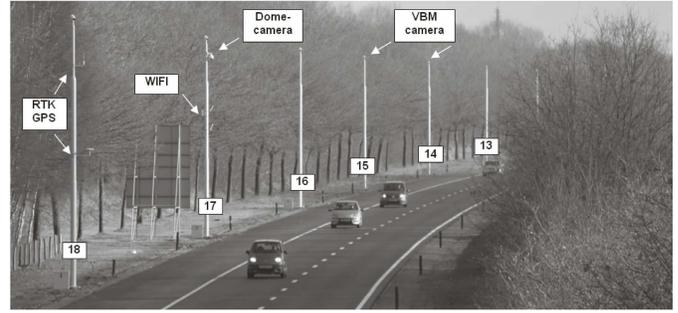

Fig. 9. Poles, intelligent roadside units, antennas, cameras, and RTK GPS transmitter along the A270 test site, which is a freeway with corresponding (small) curvatures.

For the cooperative merging scenario, vehicles are required to keep a so-called *desired* distance during platooning, balancing safety versus traffic throughput and efficiency [35]. The desired distance $d_{r,i}(k)$ of the vehicle with index i sampled at the kth discrete time instant, is given by

$$d_{r,i}(k) = r + h v_i(k) \qquad (5)$$

where r denotes the standstill distance (typically 2 to 3 meters), h the time gap (typically less than 1 second), and $v_i(k)$ the velocity of vehicle i at discrete time instance k. Desired distance is an example of an *individual* judging criterion, and applies to both competition scenarios.

Comfort, which is based on a weighted average of measured acceleration values of individual vehicles in a platoon, is an example of a *group* criterion. The average of the scores of the vehicles of a platoon is taken as the group score.

C. Judging Criteria

The three judging categories are considered below.

1) Assistance and Support (A&S): Teams are judged based on their social interaction, willingness to cooperate with and to provide feedback to other teams. Judging is performed by means of voting among teams using an automated evaluation form. For each criterion, each team ranks all the other teams by giving a distinct rank per team. The ranks for each team for all criteria are subsequently accumulated, and a scoring function applied to determine the final score.

2) Human-Machine Interaction (HMI): The shift from human driving towards automated driving inherently comes with a shift in decision making and control. For such a shift, the human-machine interaction becomes vital. As an example, in case of a planned take-over of control from vehicle to driver, the vehicle shall verify whether or not the driver is actually ready. Instead of providing strict rules for HMI, all participants were provided guidelines to enable designing and developing a human-machine interface by experts from both industry and academia. These guidelines aim at a bi-directional communication process, i.e., both from vehicle to driver as well as from driver to vehicle. A judging panel consisting of experts from academia performed the actual evaluation, based on criteria provided to the participants, see D7.1 in [42]. Participants were requested to pitch their vision
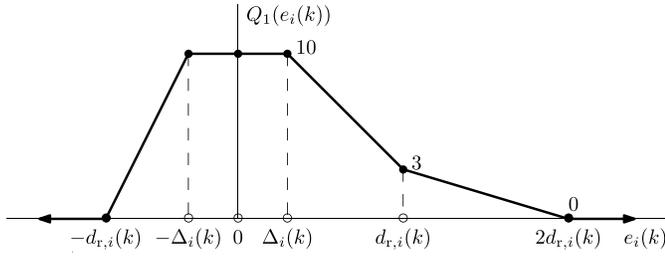
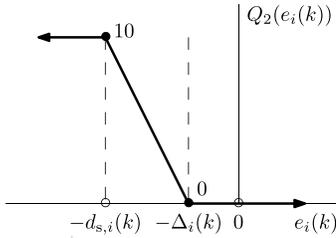Fig. 10. Scoring function Q_1 for the desired distance criterion.

Fig. 11. Penalty-scoring function Q_2 for the desired distance criterion.

on the HMI aspects of cooperative driving, supplemented with videos demonstrating specific use cases.

3) Technical Performance: To judge technical performance, a set 10 judging criteria were defined, 7 of type *individual* and 3 of type *group*, see D7.1 in [42]. For judging, desired distance, maximum speed, comfort (based on upper and lower acceleration limits), and conformance to the interaction protocol were considered, amongst others. In this paper, technical judging will only be illustrated by means of the example of desired distance. The underlying idea is that the teams shall aim at an inter-vehicle distance close to the desired distance throughout platooning, but at least maintain a safe distance. To this end, the distance error $e_i(k)$ is defined as the difference between the measured distance $d_{m,i}(k)$ and the desired distance $d_{r,i}(k)$ at time k, i.e.,

$$e_i(k) = d_{m,i}(k) - d_{r,i}(k). \qquad (6)$$

Furthermore, a threshold value $\Delta_i(k)$ is defined, according to

$$\Delta_i(k) = d_{r,i}(k) - d_{s,i}(k) \qquad (7)$$

where $d_{s,i}(k)$ is a safety distance [35]. Scoring is then based on a scoring function $Q_1(e_i(k))$ and a penalty-scoring function $Q_2(e_i(k))$, as illustrated in Fig. 10 and Fig. 11, respectively. The final score $s_{v,i}$ for vehicle i in heat v is subsequently given by

$$s_{v,i} = \max\left(0, \frac{\sum_{k \in \mathcal{K}_v} Q_1(e_i(k))}{|\mathcal{K}_v|} - \max_{k \in \mathcal{K}_v} Q_2(e_i(k))\right) \qquad (8)$$

where $\mathcal{K}_v$ is the set of time instances under consideration for heat v, and $|\mathcal{K}_v|$ denotes the cardinality of $\mathcal{K}_v$.

D. Experience and Results

Using formalized technical judging criteria to specify quality (and functional) requirements turned out to be an effective way to discuss these requirements between experts on the

TABLE III
SUMMARY OF JUDGING RESULTS

Team	A&S (10%)	HMI (20%)	Tech. (70%)	Final
6	7.9	7.4	8.7	8.4
5	8.7	4.2	9.4	8.3
1	3.9	4.2	8.3	7.1
9	9.2	5.4	7.0	6.9
3	10.0	7.4	6.0	6.7
7	6.3	6.8	6.0	6.2
4	4.9	7.8	5.8	6.1
2	8.2	4.2	5.6	5.6
10	6.3	5.4	0.0	1.7
8	–	–	–	–

one hand and between experts and participants on the other hand. Using data logged by participants' vehicles was only partially successful, however, due to lacking logs and lacking, erroneous, or inaccurate data in the logs. Automated judging was therefore complemented by visual inspection by experts through the Video-Based Monitoring (VBM) system, i.e., a system using the cameras along the A270 test site (Fig. 9), experts near the test track, and experts in the OPCs. A summary of the judging results can be found in Table III.[2]

VI. SAFETY

Safety, and consequently a safe GCDC, has received a high priority throughout the i-GAME project. However, due to the limited scope and duration of the project itself, the full ISO 26262 standard on functional safety [54] could not be followed, fully. Instead, a Hazard Assessment by Risk Analysis (HARA) was performed for the GCDC scenarios to determine which hazardous situations should be addressed by the developed systems, see D2.5 in [42].

Upon the detection of a hazard or threat by the system and/or the driver, a response is required. Examples of hazards include communication degradation in general, cut-in and emergency brake for the highway lane-reduction scenario, and a front-to-side collision for the urban intersection crossing scenario. To mitigate the consequences of failures leading to these hazards, roughly two approaches exist: Fail safety and fault tolerance. A fail-safe approach guarantees that no or minimal harm is caused to other vehicles, the environment and to people, whereas a fault-tolerant approach enables a system to continue operating properly. Since, within the scope of the GCDC, it was not considered feasible to implement fault-tolerant functionality, a fail-safe approach for a specific set of hazardous situations, including failures of the wireless communications due to, e.g., packet loss, was prescribed by the organization, involving the human driver as a backup. It was therefore mandatory that the driver should be ready to take over control throughout the competition (see D1.4 and D2.5). Consequently, the manual override mechanisms were crucial,

[2]Due to hardware-related problems, team 5 could not participate on the second day of the two-day GCDC, whereas team 8 could not participate on both days. Therefore, both teams were decided to be out-of-competition.

being 1) throttle override, 2) brake override, 3) steering wheel override, and 4) emergency button override.

To guarantee safety, the status of all vehicles from the registered teams was assessed during a safety and performance workshop held at the IDIADA proving grounds in April 2016, which was organized in three stages, see D4.1 in [42]:

1) *Documentation:* The teams had to provide a technical description of the vehicle characteristics.
2) *Inspection:* A physical inspection was performed with a special focus on the safety elements of the vehicle.
3) *Dynamic Validation:* Proving ground tests were performed to assess vehicle performance including dynamic maneuvering of the vehicle, brake tests, and override mechanisms to return control to the driver.

The teams which did not pass the tests had to take corrective actions and were subject to a re-assessment prior to the GCDC. All participating teams were able to successfully pass all safety tests and, consequently, were allowed to compete in the GCDC, see D4.6 in [42]. Moreover, no safety incidents occurred during the GCDC.

VII. Conclusion

The GCDC was organized to further advance the field of cooperative automated driving, extending platooning and CACC towards cooperative maneuvering. Here, a key aspect is the so-called interaction protocol, which defines the wireless vehicle-to-vehicle messages to be exchanged between the vehicles involved in a certain traffic scenario, allowing for coordinated execution of the desired vehicle maneuvers. However, it appeared that the current standardized message sets need to be extended to support such cooperative maneuvering.

By means of two GCDC scenarios, being a highway lane reduction and an urban intersection crossing, it was shown that the interaction protocol can be designed such that a certain level of freedom is left for the design of the vehicle control system, which is considered important to bring cooperative driving technologies closer to practical deployment.

The control approach for both scenarios, as proposed by the GCDC organization, was based on regulating inter-vehicle distances with vehicles on the adjacent lane (lane reduction) or with virtual vehicles (intersection crossing) while driving as close as possible to a set cruise speed. This is, in fact, common CACC functionality, illustrating that the concept of CACC can be extended so as to also incorporate maneuvering. This feedback-control approach has the advantage of being robust against velocity disturbances induced by other traffic. In order for the pairing (lane reduction) or target vehicle assignment (intersection crossing) prior to the actual maneuvers to be successful, it is required that the vehicle speeds in different lanes are close enough, however, without the need to control these speeds other than by means of CACC.

Since the GCDC was set-up as a competition, it also involved assessment of the teams' individual performance in a cooperative setting, which nevertheless was shown to be possible. Moreover, safety assessment of the team vehicles was an important part of the competition, from which clearly appeared that technology-agnostic tests for the

safety validation are required to be able to accommodate a wide range of automation system designs.

In summary, the GCDC event, including regular preparatory workshops, proved to be a valuable instrument to further advance the field of cooperative automated driving.

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