Cooperative Competition for Future Mobility

Ellen van Nunen, Maurice R. J. A. E. Kwakkernaat, Jeroen Ploeg, and Bart D. Netten

***Abstract*—In May 2011, the Grand Cooperative Driving Challenge (GCDC) was held, providing the possibility for teams to develop and compare their cooperative driving solutions in a competitive setting. The challenge was organized to further accelerate developments in the area of cooperative driving. Nine international teams challenged each other to handle both an urban and a highway scenario. These scenarios have been chosen such that the performance of the implementation of cooperative adaptive cruise control of each participant can be judged. Evaluation of the vehicle behavior has been performed by means of video-based roadside units, installed at the test site in The Netherlands, that is capable of tracking the individual vehicles, in addition to the information obtained through wireless communication. Judgment criteria include both macroscale criteria, such as platoon length and traffic light throughput, and individual criterion, like string stability. Most teams performed well, although clear differences in performance and reliability could be observed. The GCDC showed that it is possible to cooperatively drive with heterogeneous systems. It is envisioned to make the GCDC a regular event and to further extend the active role of roadside communication units, as well as include automated lateral vehicle control.**

***Index Terms*—Cooperative adaptive cruise control (CACC), cooperative driving.**

I. Introduction

COOPERATIVE driving is a promising technology that can significantly increase traffic throughput, limit CO_2 emissions, improve traffic safety, and increase driving comfort [1], [2]. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity allow cooperative systems to offer drivers, road authorities, and roadside infrastructure more information about vehicle's states, their intentions, and road conditions. This enables efficient and safe traffic, as well as early warnings for upcoming traffic situations (e.g., incidents and hazards).

Similar to many other densely populated regions, the road infrastructure in The Netherlands is being stretched to full capacity and beyond. As a result, congestion is a national problem; traffic jams are a regular feature all over the country. To successfully tackle traffic congestion problems, cooperation between industry, research institutes, road operators, and government is vital [3]. The Grand Cooperative Driving Challenge (GCDC) is initiated to bring these parties together and to catalyze cooperative driving technologies in an international perspective [4].

Manuscript received November 2, 2011; revised January 31, 2012 and April 27, 2012; accepted May 11, 2012. Date of publication July 6, 2012; date of current version August 28, 2012. This work was supported by High Tech Automotive Systems; the Province of North-Brabant, SRE; and the Community of Helmond. The Associate Editor for this paper was H. Nijmeijer.

The authors are with the TNO Technical Sciences, 5700 AT Helmond, The Netherlands (e-mail: ellen.vannunen@tno.nl; maurice.kwakkernaat@tno.nl; jeroen.ploeg@tno.nl; bart.netten@tno.nl).

Digital Object Identifier 10.1109/TITS.2012.2200475

Fig. 1. GCDC lead and team vehicles on the specially equipped A270 highway in Helmond, The Netherlands.

TABLE I
TEAMS PARTICIPATING IN THE GCDC 2011 (IN ALPHABETICAL ORDER)

Team name	Country
AnnieWAY	Germany
ATeam	the Netherlands
AUTOPIA	Spain
Chalmers	Sweden
FUTURUM	the Netherlands
Halmstad	Sweden
Latvia	Latvia
Mekar	Turkey, United States
Scoop	Sweden

In May 2011, HTAS [5] and TNO [6], which are two leading Dutch automotive research institutes, organized the first GCDC at the specially equipped A270 highway close to Helmond, The Netherlands, as shown in Fig. 1. The aim of the GCDC is to accelerate the introduction of cooperative vehicle technologies to significantly alleviate traffic problems and to improve traffic safety. The open competition of the GCDC invited research teams to create the best solutions and to test them during a cooperative competition on cooperative driving. As a result, teams from all over the world made their way to Helmond to compete and deliver their most effective cooperative driving system. The teams that participated in the GCDC 2011 are listed in Table I. The challenge consisted of two platooning scenarios: an urban and a highway scenario, which were chosen to evaluate the platooning capabilities of the participants.

Automated platooning has the potential to significantly increase road capacity by allowing for a small time headway (the distance between a follower and a leading vehicle divided by follower speed) while maintaining a high level of safety [7]. As the reaction time of human drivers does not allow a human driver to safely drive at such short time headways, this objective cannot be reached by simply adapting the driver style. A first important step in maintaining time headways was taken several years ago with the introduction of adaptive cruise control (ACC) [8]. ACC systems aim to achieve and maintain specified time headways, using environmental sensors—radar, lidar, or even vision-based systems—that measure the distance and relative velocity between the ACC-equipped vehicle and the preceding vehicle. Based on these measurements, the throttle and brake are automatically operated. Common ACC headway times range from 1.0 s to more than 3.0 s [9]. It is known that current ACC systems at short time headways may lead to unstable traffic behavior, which are known as string instability, i.e., amplification of disturbances in upstream direction [10]. A short braking action of a vehicle, for example, might introduce a disturbance in the platoon of vehicles, causing a shockwave that amplifies in upstream direction, finally leading to a full standstill of follower vehicles at some point or even to a collision.

A promising solution to the aforementioned string stability problem at short time headways is offered by wireless communication of vehicle motion information, such as acceleration, velocity, and position [11]. When a communication link is set up with the directly preceding vehicle, it is possible to communicate information with small delays and obtain string stable behavior. Wireless communication also opens up the possibility to look further ahead than the directly preceding vehicle and to obtain more information than onboard sensors, such as a radar, can provide. An example is vehicle acceleration or vehicle state information and information gathered by sensors of a preceding vehicle (for instance, regarding that vehicle's predecessor). The combined application of ACC-like controllers with wireless communication (V2V and V2I communication) is commonly known as cooperative ACC (CACC). One of the challenges in the process toward the large-scale deployment of CACC (but this also holds for cooperative systems in general) is to ensure safe and reliable operation. The first important aspect that contributes to this is the fault-tolerant design of the system [12]. This means that the system is equipped with several (redundant) solutions to ensure safety in case of system failure [13], particularly when wireless communication is lost. The second important aspect is graceful degradation. Graceful degradation implies that, as systems fail, the decrease in performance is proportional to the severity of the failure. Consequently, functionality gradually decreases, depending on the failure, leading to more predictable and reliable behavior.

The GCDC provides participants with a realistic environment that gives them the opportunity to test and demonstrate their innovative solutions for cooperative driving in a heterogeneous setting since participants will have implemented different solutions, driving with different vehicles. The GCDC competition explicitly targets platooning performance in terms of string stability and throughput. The last criterion not only helps lower congestion problems and increase traffic flow but also results in lower fuel consumption and lower emissions [11]. The teams were asked to develop a communicating vehicle controller incorporated into a vehicle that performs longitudinal control of the vehicle in a platooning setup. The team vehicles exchange their positions, velocities, and accelerations via wireless communication (V2x), based on IEEE 802.11p [14], [15]. In the urban and highway scenarios, V2V and V2I communication data and cooperative behavior based on video images were evaluated to judge the teams, as discussed in Sections III and IV. Since safety is a prerequisite, all teams have to guarantee a sufficient level of safety for drivers and others during the competition. The rules for safety are described in detail in [16]. The team vehicles and cooperative systems have to take part in a series of tests to assess the capability and safety of participating vehicles and cooperative systems.

The GCDC scenarios demonstrated the ability of cooperative driving to achieve objectives of reduced traffic congestion, reduced environmental impact, and—to a certain extent—improved traffic safety. The GCDC was using heterogeneous vehicles ranging from a small Smart up to large trucks. In addition, the communication hardware, the controller design, and the onboard sensors were different so that the GCDC setup resembled very much realistic future traffic scenarios. The use of heterogeneous systems is one of the strongest points of the GCDC, in comparison with previous demonstrations of platooning and V2x communication. Not only did the first GCDC contribute to the acceleration of ITS implementation in the Helmond–Eindhoven area in the Netherlands, but it also supported the development of cooperative technology in all the countries of the involved teams, ranging from the North (Sweden) to the South (Spain) of Europe and from the West (Netherlands) to the East (Turkey) as well.

Although several European projects have tended to deploy technology for cooperative systems [11], [17], [18], the development and implementation of cooperative driving technologies have seemed to stagnate to some extent, which may be due to a stalemate situation between governments and industry. Governments are waiting for industry to start to develop cooperative driving systems, whereas industry is waiting for the government to provide the required technical infrastructure. The GCDC is initiated to bring together all stakeholders and show the potential of cooperative driving in realistic scenarios on public roads.

The setup and the results of the first GCDC are described in this paper. Section II describes the competitive scenarios, i.e., the urban and the highway scenarios. In Section III, the specially equipped A270 test site is described, including the roadside units and lead vehicle. The judging methodology and the results are presented in Sections IV and V, respectively. The lessons learned are described in Section VI. Finally, conclusions and outlook are presented in Section VII.

II. Scenarios

The GCDC competition is used to assess whether participants are able to drive in a cooperative way in an urban scenario (see Section II-A), as well as in a highway scenario (see Section II-B). It takes place at a highway, as described in Section III, which is also equipped with two traffic lights.

The participants are positioned on a highway in two lanes (left lane and right lane, see Fig. 2). Participants in one lane challenge the participants in the other lane. The lead vehicle is positioned at the middle of the lanes and is followed by the participants. The lead vehicle broadcasts its position, velocity, and acceleration via wireless communication. The number of vehicles in each lane is the same. The assignment of each vehicle to a lane and its position in the lineup are chosen by the GCDC 2011 organization such that each participant is challenged at least once in the most crucial positions. Consequently,

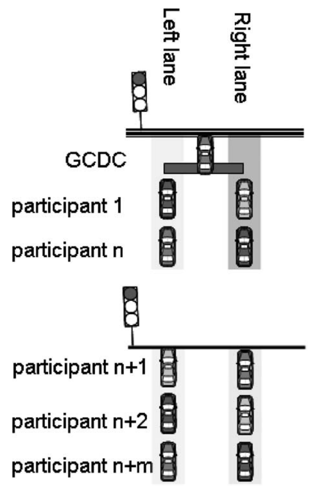


Fig. 2. Vehicle positioning at the start of a heat.

the scenario is executed multiple times with different vehicle orderings; each test is referred to as a "heat." When each heat starts, the teams have to complete a scenario, consisting of an urban part and a highway part. After each heat, the assignment to a team and the position of each participant in the lineup are changed, so that each vehicle is positioned in different lanes and takes different positions in the lineup during the heats.

A. Urban Part of the Scenario

The urban scenario is presented by two traffic lights, as shown in Fig. 2. The objective is twofold: First, the platoon of vehicles waiting at a red traffic light downstream should maximize throughput at this traffic light by communicating and accelerating in a coordinated way when the light turns green. Second, a platoon further upstream attempts to smoothly join the platoon of vehicles driving away from the downstream traffic light. This latter aspect concerns interplatoon behavior. The urban part can be described by the following steps.

1) At the start, a number of participant vehicles $n+1,\ldots,n+m$ is lined up at the upstream red traffic light. The objective of the vehicles in each lane is to cooperatively accelerate through this traffic light once the light turns green, as shown in Fig. 3. A number of other participant vehicles $1,\ldots,n$, led by a GCDC vehicle, are waiting for the downstream traffic light at a predefined distance (see Fig. 2).
2) At the start of the heat, the upstream traffic light turns green, and participant vehicles $n+1,\ldots,n+m$ start driving, as shown on the left side of Fig. 3. The participants in the two lanes try to maintain a stable platoon. The time-to-green of both traffic lights is communicated by roadside units.
3) When the downstream traffic light, where participant vehicles $1,\ldots,n$ are waiting, turns green, the GCDC lead vehicle starts driving with a predefined velocity profile [see the center of Fig. 3]. The participant vehicles should automatically accelerate as well, using the cooperative information communicated among the GCDC vehicle and other vehicles as well as their cooperative vehicle controllers.
4) Participant vehicles $n+1,\ldots,n+m$ try to join vehicles $1,\ldots,n$, while maintaining platoon stability. The urban part of the scenario ends when the last vehicle of either the left or right lanes crosses the finish line [see the right side of Fig. 3].

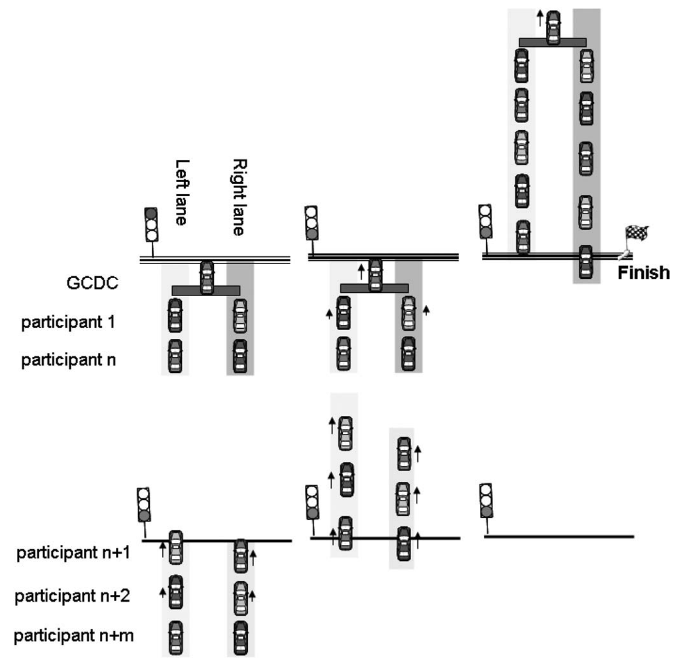


Fig. 3. Urban challenge: Cross the finish line with the team as fast as possible while maintaining safety rules.

B. Highway Part of the Scenario

The highway scenario tests the participants' ability to maintain a stable platoon. The objective is to demonstrate "ideal" intraplatoon behavior. Ideal behavior concerns the optimization of the distance between vehicles toward throughput improvement while driving safely and at varying speeds. This requires reacting to disturbances within the platoon in such a way that disturbances are attenuated and shockwaves are avoided. The description of the highway scenario is given as follows.

1) The highway part of the competition scenario starts when the urban part ends. Both parts of the scenario are executed in one single heat. Thus, the right side of Fig. 3, which shows the end of the urban part, also represents the start of the highway part.
2) After the first team has reached the finish line, the GCDC vehicle remains a constant speed for some time. Then, the GCDC vehicle introduces disturbances, which enable judging string stability: the ability to dampen shockwaves. The task of the participants is to maintain a coherent and string stable platoon while not compromising safety. In addition, the platoon length should be minimized, as explained in Section IV. Again, the vehicles

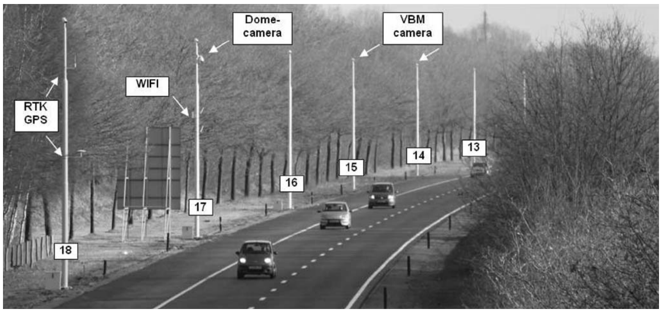


Fig. 4. Poles, roadside units, antennas, cameras, and RTK GPS transmitter along the A270 test site.

fully automatically operate in the longitudinal direction only. Hence, the driver must steer.

3) The heat ends in standstill.

III. Test Site

The GCDC 2011 competition takes place on the A270 Test Site, which is located on the westbound A270 highway between the cities of Helmond and Eindhoven in The Netherlands. This 6-km-long highway has been closed off for several days of testing and for the challenge days. The test site is equipped with a roadside infrastructure, a test management center (TMC), and instrumented vehicles, such as the lead vehicle.

A. Roadside Infrastructure

The test site has an infrastructure along the road side, as shown in Fig. 4. There are 48 fixed video cameras, nine dome cameras, 12 gateways for 802.11p-based wireless communication, and one real-time kinematic (RTK) Global Positioning System (GPS) base station, all connected via a fiber-optic network to the TMC. The dome cameras are primarily used for monitoring the safety and test progress at the test site.

The fixed cameras are mounted on 10-m-high poles at intervals of 100 m and provide the input to the video-based monitoring (VBM) system [19]. Fig. 5 shows a screen shot from the fixed camera at the second traffic light. VBM detects and tracks all vehicles in real time along the highway and provides a set of trajectories with the position and speed for each vehicle at 10 Hz (see Figs. 7–10). The VBM trajectories provide the objective measurements for judging the performance of participants throughout the heats, as discussed in Section IV. The real-time trajectories from VBM are processed for scoring and judging after each heat. The accuracy depends on the distance to the cameras among others. At a distance of 100 m from a camera, the position accuracy is estimated to be typically within 1 m, and the speed accuracy is estimated to be less than 0.5 m/s during modest accelerations and 1 m/s during acceleration peaks [20].

The VBM trajectories also provide the data to maintain a dynamic map of all vehicles on the A270. This map of momentary vehicle positions and speeds is broadcasted via the 12 communication gateways from the road side at 10 Hz, with a delay of 500 ms, to provide the GCDC vehicles an objective reference map for their navigation and longitudinal control, e.g., in case of any disruptions in communication or positioning. It should be noted that, unlike in other cooperative systems tests as presented in [19], the information received from the GCDC vehicles via the wireless communication is not fused with the VBM data to maintain the objectivity of the measurement system for GCDC.

Fig. 5. Fixed camera capturing the finish line of the urban scenario for the left team with VBM in heat 15 (cf. Fig. 9).

The TMC has the functionality to monitor and control the tests, manage test site safety, and log all data from the roadside equipment. The TMC broadcasts the messages to the vehicles to start, stop, or abort heats. The TMC also controls the traffic lights and broadcasts the time-to-green messages to the participant vehicles and runs the scripts for judging participants' performance and scoring.

B. Lead Vehicle

The lead vehicle is a Citroen C4, which sends its own vehicle state information (position, velocity, and acceleration) to the participants. During the competition, the lead vehicle drives at the middle of the two lanes, at the center line of the road. The vehicle is modified such that it can automatically drive a specified velocity profile, as shown in Fig. 6, repetitively. The lead vehicle is shown on the right side of Fig. 1.

IV. Judging

A challenging aspect of the GCDC is how to define judging criteria in a competition that is based on cooperation. The main goal of CACC is to improve throughput and thereby make better use of the road capacity. Throughput is typically measured at macroscale, whereas a competition requires a winner and, therefore, requires microscale (individual) criteria.

A participant is very dependent on the performance of others driving in the same platoon. In case another participant does not perform well in a platoon, all participants in that platoon lose on macroscale criteria. However, when start positions are randomly chosen and enough heats are executed, macroscale criteria could still lead to the best performing participant. For

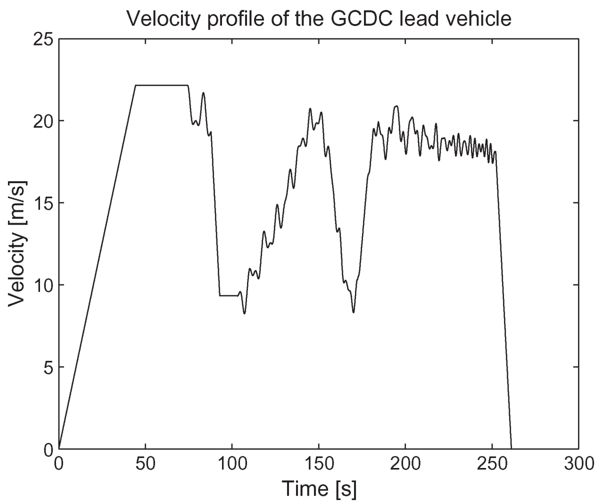


Fig. 6. Velocity profile of the GCDC lead vehicle for the highway scenario.

example, when the probability that the best performing participant would win a heat, based on the macroscale criteria would equal 0.6, more than 170 heats would be required to deduce the winner with a probability of 0.998. However, there is only a limited amount of heats (i.e., 20 heats) to be done. Therefore, an individual criterion is required, which contributes for a large part in the final score.

It is chosen to define two criteria for measuring the throughput of the whole platoon (traffic light throughput and maximum platoon length, based on VBM measurements) and one individual criteria: string stability (based on communicated velocities). These criteria are explained in this section. In Section V, the judging criteria are applied to the results of a heat.

The participants are judged on the following aspects.

Throughput at Traffic Lights: the platoon length at the time at which the last vehicle of a team passes the finish line in the urban part of the scenario is measured. Since the teams might not have the same nominal length due to differences in vehicle length, the following method is used to judge this aspect: The platoon length $L_p(t)$ at the moment the last vehicle passes the finish line equals

$$L_p(t_1) = x_{\text{lead}}(t_1) - x_f \tag{1}$$

where $x_{\text{lead}}(t)$ is the rear bumper of the GCDC lead vehicle position (from VBM measurements) at time t, t_1 is the time at which the rear bumper of the last vehicle of a team passes the finish line, and x_f is the position of the finish line. To compensate for the differences in vehicle lengths, the platoon length is expressed as the total gap length L_g given by

$$L_g(t_1) = L_p(t_1) - \sum_{i=2}^{m} L_i \tag{2}$$

where L_i is the length of vehicle i. The platoon vehicles are enumerated from 1 to m, with 1 being the GCDC lead vehicle and m indicating the last platoon vehicle.

Maximum Gap Length: $L_{g,\max}$ reached during the highway scenario, which is defined according to

$$L_{g,\max} = \max_{t\epsilon[t_2,t_3]} \left(L_p(t) - \sum_{i=2}^{m} L_i \right) \tag{3}$$

where $L_p(t)$ is the total platoon length measured from the front bumper of the GCDC lead vehicle to the front bumper of the last vehicle at time t. The number of vehicles in the platoon is represented by m. t_2 and t_3 indicate the start and stop times of the highway scenario, respectively. This criterion thus measures the maximum platoon length, corrected for the vehicle length, such that differences in vehicle lengths between teams do not influence the criterion value.

String Stability: Individually judged during the highway scenario. String stability is a measure of the ability to dampen shockwaves and thereby improve throughput. For the definition of string stability used here, see [21] and [22]. A shockwave is dampened if the acceleration of vehicle $i-1$ is not amplified by its following vehicle i: This behavior can be verified using different types of norms. Two approaches are shortly described to define string stability of a system.

1) A system is $\mathcal{L}_2$-string stable if the $\mathcal{L}_2$-norm of the velocity $v_{i-1}(t)$ of vehicle $i-1$ is larger or equal to the $\mathcal{L}_2$-norm of the velocity $v_i(t)$ of vehicle i, i.e.,

$$\|v_i(t)\|_{\mathcal{L}_2} \leq \|v_{i-1}(t)\|_{\mathcal{L}_2} \, \forall \, i \, \epsilon \, \mathbb{N} - \{1\}. \tag{4}$$

This should hold for all $v_{i-1} \epsilon \, \mathbb{R}^n$, in which n is the size of v_{i-1}. In practice, one cannot check all possible v_{i-1} nor find a specific case for v_{i-1}, which covers all others. Thus, (4) is simplified using the following property:

$$\frac{\|v_i(t)\|_{\mathcal{L}_2}}{\|v_{i-1}(t)\|_{\mathcal{L}_2}} \leq \|\Gamma_i(j\omega)\|_{H_\infty} \tag{5}$$

in which $\Gamma_i(j\omega)$ represents the transfer function between input v_{i-1} and output v_i in the Laplace domain evaluated along the imaginary axis. However, this property is not conservative since, for each system, there is always v_{i-1} such that the equality is met. When stating

$$\|\Gamma_i(j\omega)\|_{H_\infty} \leq 1 \tag{6}$$

it follows that

$$\|v_i(t)\|_{\mathcal{L}_2} \leq \|v_{i-1}(t)\|_{\mathcal{L}_2} \, . \tag{7}$$

Thus, (6) is a necessary condition for $\mathcal{L}_2$-string stability. However, in practice, the only way to estimate $\|\Gamma_i(j\omega)\|_{H_\infty}$ is to include many frequencies in the input signal. Therefore, the velocity profile of the GCDC lead vehicle was chosen to be a sum of three swept sines, such that the relevant frequencies (0.01 rad/s–2 rad/s) were captured (around 100–250 s in the velocity profile presented in Fig. 6). However, since the highway scenario was approximately 4.5 km, the duration of each frequency was very short, implying a less-accurate estimation of $\|\Gamma_i(j\omega)\|_{H_\infty}$. Unfortunately, the inaccuracy of this estimation was too high to give a reliable comparison between the participants.

2) A system is $\mathcal{L}_\infty$-string stable if

$$\|v_i(t)\|_{\mathcal{L}_\infty} \leq \|v_{i-1}(t)\|_{\mathcal{L}_\infty} \; \forall \, i \, \epsilon \, \mathbb{N} - 1. \quad (8)$$

Here, again, this should hold for all $v_{i-1} \epsilon \, \mathbb{R}^n$. When assuming linear models, the overshoot of the velocity of vehicle i with respect to the velocity of vehicle $i-1$, as a response on a step, as shown in Fig. 6, around 90–100 s, enables ranking of the participants in string stability.

The second approach for string stability is chosen since an accurate estimation of $\|\Gamma_i(j\omega)\|_{H_\infty}$ was not possible. Note that the above string stability cannot always be applied in case of mixed communication structures. Therefore, only vehicles in selected platoon positions are judged, being the first vehicles at the left and right lanes after the GCDC lead vehicle. The positioning for the lineup is chosen such that each participant is in one of these first positions at least two times.

At the end of each heat, when both the urban finish line and the maximal platoon length are won by the same team, each participant in the winning team receives one point. At the end of the competition, when each participant has been challenged on the individual criterion, the participants are ranked toward their performances on string stability. The participant that performs best in string stability receives seven points, the next six points, etc. The total sum of the platoon scores and the individual scores lead to the final score. The winner is the team with the highest score and receives the GCDC 2011 cup.

V. Results

The judging criteria are applied to the results of heat 15. The position–time plots of each participant are shown in Figs. 7 and 8. Here, one can see that a large gap between two vehicles is formed in the right lane. The road capacity is better used in the left lane, where the desired gaps were maintained. It is therefore expected that the left lane wins this heat.

Throughput at Traffic Lights: The position–time plots of the left and right lanes are shown in Figs. 9 and 10, respectively. The finish line is positioned at 1253.6 m. The platoon length for the left lane at the moment its last vehicle passes the finish line equals $L_p(t_1) = 101$ m. Applying (2) to compensate for the vehicle lengths leads to $L_g(t_1) = 101 - 20.1 = 80.9$ m. For the right lane, the platoon length equals $L_p(t_1) = 140$ m. Compensation for the vehicle lengths leads to $L_g(t_1) = 140 - 20.9 = 119.1$ m. This means that, for this heat, the left lane wins the finish-line challenge.

Maximum Gap Length: Figs. 11 and 12 show the platoon lengths L_p and the corrected platoon lengths L_g during time of the left and right lanes, respectively. The maximum platoon length of the left lane equals 110.3 m, whereas this value for the right lane equals 446.7 m. The winner of this judging criteria for this heat is thus the left lane.

String Stability: For each participant, the overshoot in velocity, as a measure for string stability, is determined when its start position was directly after the GCDC lead vehicle. As an example, the overshoot in velocity of team Annieway is shown

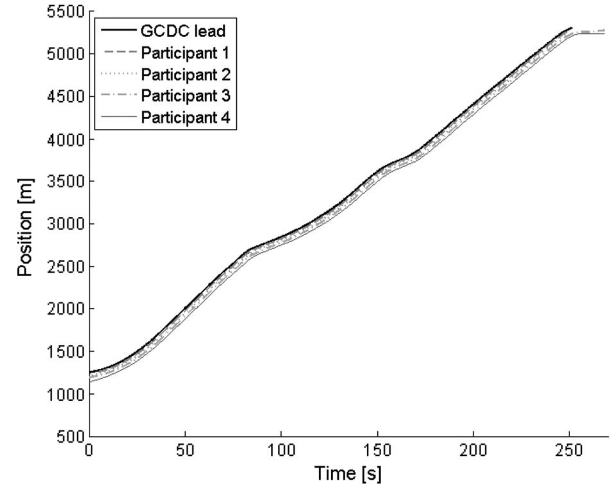


Fig. 7. Trajectory of the left team of heat 15 measured with VBM.

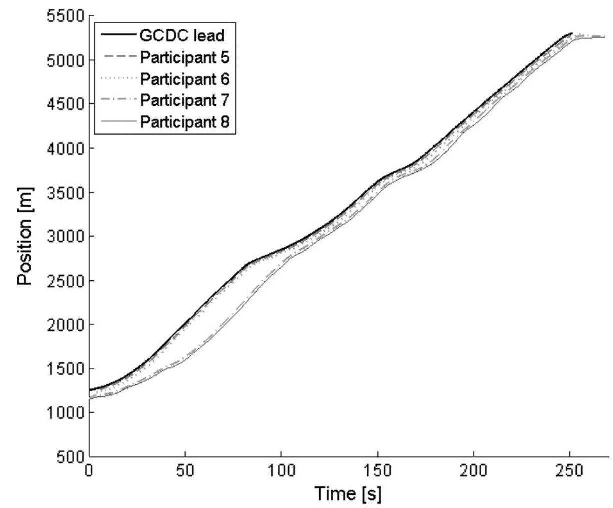


Fig. 8. Trajectory of the right team of heat 15 measured with VBM.

in Fig. 13. This is the lowest overshoot measured during the competition.

In heat 15, the left lane wins both the throughput at traffic lights criteria and the maximum gap length criteria. Thus, each participant in the left lane receives one point for this heat. After all heats and the ranking of string stability, the total number of points can be counted, leading to the winner. The GCDC 2011 cup is won by team Annieway.

VI. Lessons Learned

During the preparation and execution of the GCDC, several organizational and technical matters appeared to be of importance. An organizational matter, for example, includes the organization of a workshop on V2X communication and the possibility to test CACC among participants. A few months before the GCDC took place, a workshop was organized to test the implementation of the communication of each participating team. This appeared to be essential for a smooth start of the GCDC, without time-consuming technical communication problems.

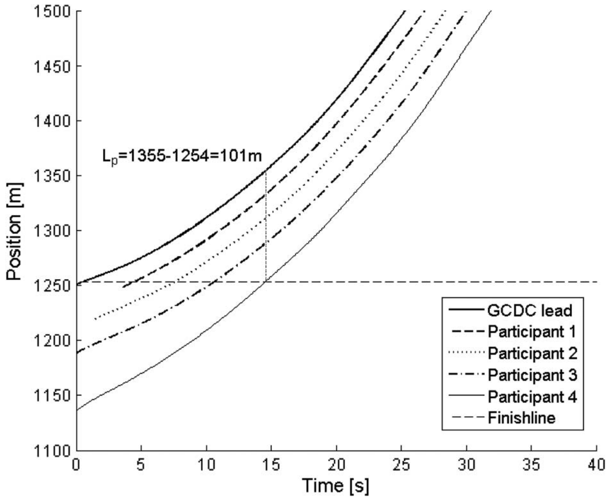


Fig. 9. Platoon length at the moment the last vehicle crosses the finish line (left team, heat 15) measured using VBM data.

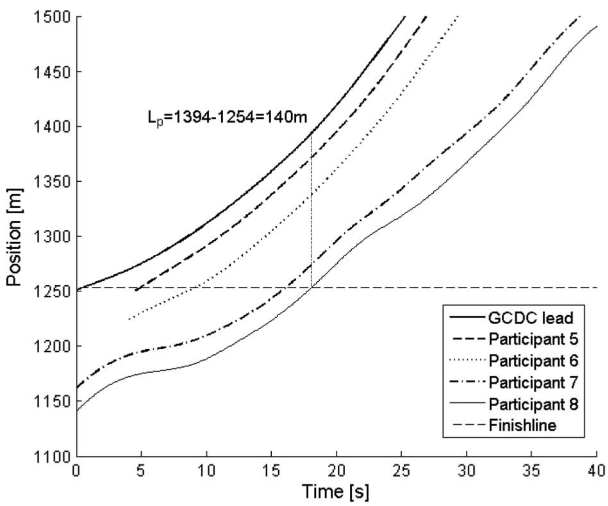


Fig. 10. Platoon length at the moment the last vehicle crosses the finish line (right team, heat 15) measured using VBM data.

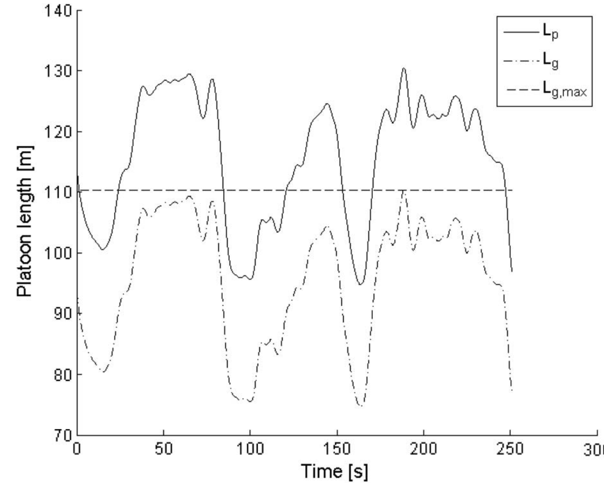


Fig. 11. Maximum platoon length of the left team of heat 15 calculated using VBM data.

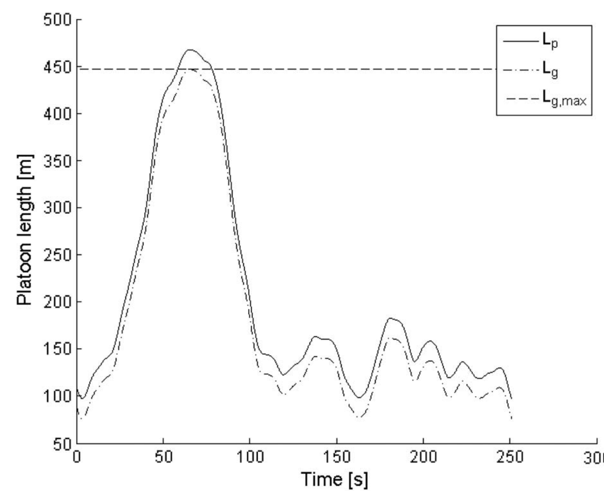


Fig. 12. Maximum platoon length of the right team of heat 15 calculated using VBM data.

Furthermore, the definition of the scenarios and judgment criteria to evaluate CACC in a cooperative competition was a technical challenge. To include the cooperative part while deducing an individual winner, a mix of cooperative criteria and individual criteria was necessary. For the individual criterion (string stability), several approaches seemed to be possible, but in practice, only one approach appeared to be feasible.

Due to the different levels of maturity, which are seen within the participants, it became clear that robustness and safety were even more important than many participants originally thought. When a participant had problems, another participant needed to anticipate.

The most important lesson learned is that, for heterogeneous systems, it is indeed possible to operate cooperatively, using very different control solutions.

VII. Conclusion and Outlook

The GCDC provides a stimulating environment for participants from research, industry, and academia to accelerate the development of cooperative and automated driving technologies through "cooperative competition." As such, industry, government, and research partners are brought together to collaborate on intelligent transportation systems solutions, ultimately creating a European community on cooperative driving developments. Furthermore, the GCDC contributes to an increased public awareness regarding these technologies and specifically their potential with respect to throughput, safety, and environmental aspects. From a technical perspective, a basis has been provided for the development of wireless communications between vehicles and roadside infrastructure, focusing on IEEE 802.11p-based communication protocol stacks. In addition, real-time control solutions for networked systems can be evaluated and compared. It is envisioned to make the GCDC a regular event, extending to a more active role of roadside units and automated lateral vehicle behavior in the next version.

Acknowledgment

The authors would like to acknowledge all people and organizations that supported the first GCDC.

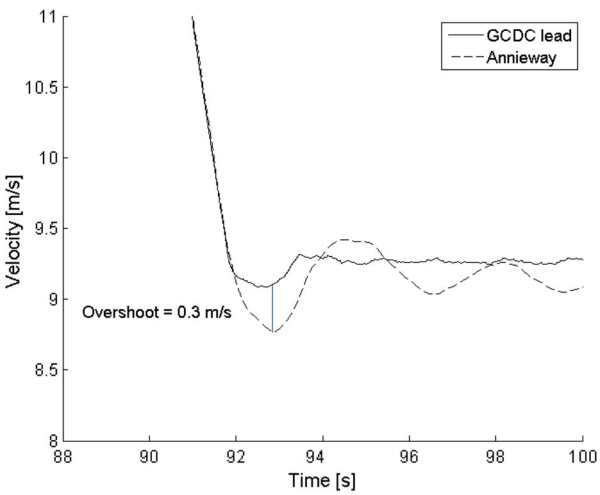


Fig. 13. Part of the velocity profiles of the GCDC lead vehicle and team Annieway.

REFERENCES

[1] "Information and communications technologies for safe and intelligent vehicles," Communication From the Commission to the Council and the European Parliament, p. 963, 2003, no. SEC(2003).

[2] S. Cheon, "An overview of automated highway systems (ahs) and the social and institutional challenges they face," Univ. California Transp. Center, Berkeley, CA, Spring 2003.

[3] "Nota mobiliteit: Naar een betrouwbare en voorspelbare bereikbaarheid," Ministerie van verkeer en waterstaat, Sep. 30, 2004.

[4] GCDC Website. [Online]. Available: www.gcdc.net

[5] *HTAS: The Dutch Automotive Innovation Programme*. [Online]. Available: www.htas.nl

[6] *TNO: Netherlands Organisation for Applied Scientific Research TNO*. [Online]. Available: www.tno.nl

[7] B. van Arem, C. van Driel, and R. Visser, "The impact of cooperative adaptive cruise control on traffic-flow characteristics," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 429–436, Dec. 2006.

[8] J. VanderWerf, S. Shladover, M. Miller, and N. Kourjanskaia, "Evaluation of the effects of adaptive cruise control systems on highway traffic flow capacity and implications for deployment of future automated systems," in *Proc. 81st Annu. Meeting Transp. Res. Rec.*, 2003, pp. 78–84.

[9] *Transport Information and Control Systems—Adaptive Cruise Control Systems—Performance Requirements and Test Procedures, ISO 15622*, Int. Org. Standardization Std. ISO 15 622, Oct. 2002.

[10] D. Swaroop and J. Hedrick, "String stability of interconnected systems," *IEEE Trans. Autom. Control*, vol. 41, no. 3, pp. 349–357, Mar. 1996.

[11] W. Schakel, B. van Arem, and B. Netten, "Effects of cooperative adaptive cruise control on traffic flow stability," in *Proc. 13th Int. IEEE Conf. ITSC*, 2010, pp. 759–764.

[12] J. Spoonert and K. Passinot, "Fault tolerant longitudinal and lateral control for automated highway systems," in *Proc. Amer. Control Conf.*, Seattle, WA, Jun. 21–23, 1995, pp. 663–667.

[13] A. Manzone, A. Pincetti, and D. De Costantini, "On-line testing workshop, 2001," in *Proc. 7th Int. On-Line Testing Workshop*, Taormina, Italy, Jul. 9–11, 2001.

[14] *Draft Amendment for Wireless Access in Vehicular Environments (WAVE)*, IEEE Std. P802.11p/D11.0, Apr. 2010.

[15] *ETSI TC ITS Intelligent Transport Systems (ITS): European Profile Standard and Medium Access Layer of 5 GHz ITSs*, Draft ETSI ES 202 663 V0.0.6, Oct. 2009.

[16] *GCDC 2011 Rules and Technology Document Final Version 2.0 (April 12, 2011)*. [Online]. Available: www.gcdc.net/mainmenu/Home/technology/Rules_and_Technology

[17] J. Spoonert and K. Passinot, "Starting european field tests for car-2-x communication: The drive C2x framework," in *Proc. 18th ITS World Congr. Exhib.*, Orlando, FL, Oct. 16–20, 2011.

[18] G. Vivo, "The safespot integrated project: An overview," in *Proc. IEEE Intell. Veh. Symp.*, 2007, p. 14.

[19] J. Baan, "Spits road side sensor system," in *Proc. 8th ITS Eur. Congr.*, Lyon, France, 2011.

[20] C. van Leeuwen, "Driver modeling and lane change maneuver prediction," Univ. Groningen, Oranjewijk, The Netherlands, Oct. 2010.

[21] G. J. L. Naus, R. P. A. Vugts, J. Ploeg, M. J. G. van de Molengraft, and M. Steinbuch, "String-stable CACC design and experimental validation: A frequency-domain approach," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010.

[22] J. Ploeg, B. T. M. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," in *Proc. 14th Int. IEEE Conf. Intell. Transp. Syst.*, Wahington, DC, Oct. 5–7, 2011, pp. 260–265.

Ellen van Nunen was born in 1981. She received the M.Sc. degree in applied mathematics from Eindhoven University of Technology, Eindhoven, The Netherlands, in 2004.

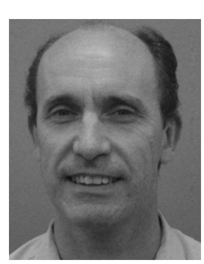
From 2005 to 2007, she was a Verification Consultant with the Department Electronic Design and Tools (currently NXP), Philips. Since 2007, she has been a Research Scientist with TNO Technical Sciences, Helmond, The Netherlands, working in the automotive field. Her current interests focus on cooperative driving systems, fail safety, and fault-tolerant systems.

Maurice R. J. A. E. Kwakkernaat was born in 1978. He received the Ph.D. and M.Sc. degrees in electrical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, in 2004 and 2008, respectively. His Ph.D. research included high-resolution propagation measurements and modeling of mobile wireless channels.

Since 2009, he has been a Research Scientist with TNO Technical Sciences, Helmond, The Netherlands. His current research interests include cooperative driving systems, sensor technology for mobility applications, and mobile and wireless communication technology.

Jeroen Ploeg was born in 1964. He received the M.Sc. degree in mechanical engineering from Delft University of Technology, Delft, The Netherlands, in 1988. He is currently pursuing the Ph.D. degree with the Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands, working on the synchronization of road vehicles for cooperative driving, which is also known as cooperative adaptive cruise control, with focus on the stability and performance of strings of vehicles.

From 1989 to 1999, he was a Researcher with Koninklijke Hoogovens (currently Corus), IJmuiden, The Netherlands, where his main interest was dynamic process control of large-scale industrial plants. Since 1999, he has been a Senior Control Engineer with TNO Technical Sciences, Helmond, The Netherlands. This work was executed in close cooperation with the Department of Mechanical Engineering, Eindhoven University of Technology. His current research interests are control system design for advanced driver-assistance systems and cooperative driving systems.



Bart D. Netten was born in 1964. He received the M.Sc. degree in aerospace engineering and the Ph.D. degree in artificial intelligence from Delft University of Technology, Delft, The Netherlands, in 1988 and 1997, respectively.

From 1990 to 1993, he was a Researcher with the Automatic Control Laboratory, University of Ghent, Gent, Belgium. From 1994 to 1999, he was a Researcher with the Faculty of Mathematics and Electronics, Delft University of Technology. Since 2000, he has been a Research Scientist with TNO Technical Sciences, Helmond, The Netherlands, working in the field of cooperative systems, traffic monitoring, and roadside systems.