Introduction to the Special Issue on the 2011 Grand Cooperative Driving Challenge

INTRODUCTION

IN May 2011, The Netherlands Organization for Applied Scientific Research TNO, together with the Dutch High Tech Automotive Systems innovation program (HTAS), organized the Grand Cooperative Driving Challenge (GCDC) in The Netherlands. The underlying objective was to increase momentum regarding the deployment of cooperative driving, focusing on real-time applications. To this end, the 2011 GCDC focused on a specific type of cooperative driving: cooperative vehicle following with a short intervehicle distance, commonly known as cooperative adaptive cruise control (CACC). The main reason to focus on CACC is the promise of a significant increase in road capacity (throughput) and corresponding decrease in fuel consumption without compromising safety. From earlier studies (see, e.g., [1] and [2]), it is expected that throughput may increase at least 10%. Depending on conditions such as the degree of market penetration, benefits may be significantly larger.

Nine international teams participated in the challenge (see Fig. 1). In addition to numerous practical aspects, the teams had to address three key aspects relevant to the implementation of real-time cooperative driving applications, as summarized here.

Robust Fail-Safe Real-Time Control

The concept of automated vehicle following with road vehicles has been well known for decades. One of the first control-oriented publications on the subject, yet without addressing the characteristics of wireless communications, dates back to 1966 [3]. Since then, a large amount of relevant research has been published (see [4]–[6] and references contained therein). A frequently adopted approach is based on well-defined vehicle platoons, in the sense that all vehicles have equal (or at least known) dynamics and that a platoon leader is present. As opposed to this structured environment, the GCDC addressed the application of automated vehicle following in everyday traffic, which is characterized by an unstructured environment consisting of vehicles of various types and instrumentation. Moreover, in practice, a natural platoon leader need not be present. The latter can be handled by either implementing a negotiation mechanism to determine the platoon leader and the platoon members, thereby increasing the communication load, or an "ad hoc vehicle following" approach, which is characterized by a
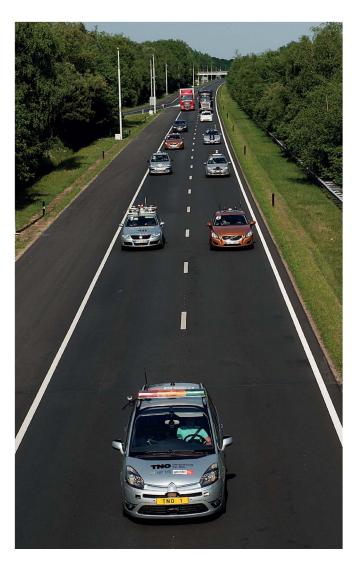

Fig. 1. GCDC participants with the organization's lead vehicle.

cluster of cooperative vehicle followers without a leader (and known members). Research into these implementation-relevant aspects has emerged only recently (see, e.g., [7] and [8]).

Application in everyday traffic also requires a high level of reliability and safety. CACC heavily depends on wireless communication, which will require careful network planning and message handling to achieve the necessary reliability. A high level of redundancy might not be the *a priori* solution since this also increases system costs. Consequently, a carefully designed system, achieving a sufficient level of reliability and a mechanism for graceful degradation to ensure safety, while keeping system costs to a minimum, is the actual challenge that has yet to be solved. In the GCDC, safety and reliability were specified only at a functional level, leaving the actual implementation

to the participants. As a result, various solutions were developed, based on very different hardware and software.

Finally, although the GCDC did not explicitly challenge user aspects, user acceptance and behavior are important aspects to be addressed before a safety-critical cooperative driving application, such as CACC, can be employed [9].

Distributed Real-Time Information Structures

Cooperative driving technologies rely to a large extent on information exchange between traffic participants and/or between traffic participants and roadside units. To cooperate successfully, communicating nodes must have a common understanding of the exchanged information. Standardization of message formats and communication and interaction protocols is therefore part of the solution [10].

Road users and roadside units fuse data from their own sensors and from communication to construct their local view of the world or "world model." A world model includes a representation of the local traffic situation and the status of neighboring vehicles and roadside units and provides the input for control [11].

On a traffic level, road users and roadside units have to maintain some level of consistency in the distributed world view to support cooperative (and safe) behavior. Consequently, a complex large-scale information flow arises, exchanging motion data and events on a real-time basis. This requires a well-defined information architecture, achieving a high level of reliability and scalability.

While developing the GCDC, it appeared that the aforementioned issues could only be addressed with a well-defined interaction protocol, including the standardization of message content, which is adopted by all participants. The GCDC organization was responsible for the development of the interaction protocol, which took place in close cooperation with the participants.

Wireless Communication in Real-Time Environments

It is well known that wireless and mobile communications are subject to failure by their very nature. Examples of phenomena, impeding flawless communications, are varying signal strengths due to varying propagation conditions; multipath fading, including intersymbol interference; Doppler shifts due to station mobility; and many types of interference signals, such as man-made noise and intermodulation [12]. In ad hoc networks, including vehicle-to-vehicle networks, where stations communicate without the use of fixed infrastructure, additional problems arise; for instance, transmitting stations may cause mutual interference at a receiver without knowing it (hidden terminal problem [13]). The latter problem actually becomes more dominant in the typical future setting envisioned in the GCDC, in which vehicles exchange motion data at relatively high update rates (10 Hz or higher) and require low latencies (significantly less than 100 ms).

Despite a plethora of mitigation strategies found in modern wireless communication systems, none of these are fail-safe. The control system should therefore be robust against wireless communication impairments such as latency, fading, frame and packet loss, and limited range and bandwidth. A careful balance is needed between the use of and dependence on information obtained through wireless communications and the use of on-board sensors to obtain the required situation awareness and to assure safety at all times. Finding this balance is an important objective of the GCDC in view of large-scale deployment, which is more important than the communication technologies by themselves.

SCANNING THE ISSUE

This Special Issue contains the contributions of six participating teams from academia and industry, together providing a comprehensive overview of the different approaches that one might take with respect to the technical aspects of CACC, such as wireless communications, object tracking, controller design, and vehicle instrumentation. Each paper will be briefly introduced here, starting with an introductory paper about the technical aspects of organizing the challenge. Note that the participant papers are listed in the order corresponding to their final ranking in the 2011 GCDC.

"Cooperative Competition for Future Mobility" by E. van Nunen, M. R. J. A. E. Kwakkernaat, J. Ploeg, and B. D. Netten

This paper serves as an introduction to the Special Issue, describing the challenge scenarios, the judgment criteria, and the use of roadside equipment to obtain judgment data. Judging individual participants that are supposed to act in a cooperative setting is not particularly easy, if not a *contradictio in terminis*. Nevertheless, two scenarios were found suitable, i.e., an urban and a highway scenario, based on which each participant's behavior could be quantitatively judged, using string stability, gap length, and throughput at traffic lights as criteria.

"Team AnnieWAY's Entry to the 2011 Grand Cooperative Driving Challenge" by A. Geiger, M. Lauer, F. Moosmann, B. Ranft, H. Rapp, C. Stiller, and J. Ziegler

The contribution of the winning team from Karlsruhe Institute of Technology to the Special Issue gives an excellent overview of all systems involved in automated vehicle following: not only control but also vehicle-to-vehicle communication, onboard sensors (among which radar), and sensor fusion as well. Furthermore, the issue is raised of how to deal with inaccurate communicated data of other vehicles, which is a topic that is rarely addressed.

"A Modular CACC System integration and Design" by K. Lidström, K. Sjöberg, U. Holmberg, J. Andersson, F. Bergh, M. Bjäde, and S. Mak

The Halmstad University team applied a highly modular system architecture that enables rapid development and testing of the various subsystems, which led to a full development-testing cycle of only nine months. An adaptive cruise control (ACC)-equipped production vehicle appeared to provide an excellent basis for CACC since such a platform is already computer-actuated and includes most, if not all, of the required onboard sensors.

"Design and Experimental Validation of a Cooperative Driving System in the Grand Cooperative Driving

Challenge" by R. Kianfar, B. Augusto, A. Ebadighajari, U. Hakeem, J. Nilsson, A. Raza, R. S. Tabar, N. V. Irukulapati, C. Englund, P. Falcone, S. Papanastasiou, L. Svensson, and H. Wymeersch

Chalmers University, like the previous teams, also identified three main components in the CACC system, i.e., communication, implementing the 802.11p-based CALM FAST standard; sensor fusion to track other traffic participants; and control to implement the vehicle-following behavior. As far as the control is concerned, a linear controller and a Model Predictive controller have been designed and compared, notably without a clear "winner."

"The Development of a Cooperative Heavy-Duty Vehicle for the GCDC 2011: Team Scoop" by J. Mårtensson, A. Alam, S. Behere, M. A. A. Khan, J. Kjellberg, K.-Y. Liang, H. Pettersson, and D. Sundman

The Scoop team, which is a collaboration between the Swedish KTH Royal Institute of Technology and Scania CV AB, participated with one of the largest road freight trucks currently commercially available. Although the GCDC scenarios were designed to suit trucks as well, particularly regarding maximum acceleration, probably the biggest challenge with respect to longitudinal truck control is the large amount of gear shifts, during which the truck is effectively uncontrolled. Nevertheless, this team performed rather well, showing that a mixed truck–passenger vehicle platoon is feasible. The paper explicitly addresses fail safety, which was implemented by gradually decreasing the functionality from CACC via ACC to cruise control, depending on the availability of platoon information. An important conclusion is that it is possible, with modest effort, to design and implement a system that can function well in cooperation with other vehicles in realistic traffic scenarios.

"Cooperative Driving with a Heavy-Duty Truck in Mixed Traffic: Experimental Results" by M. R. I. Nieuwenhuijze, T. van Keulen, S. Öncü, B. Bonsen, and H. Nijmeijer

The ATeam, from Eindhoven Technical University, also participated with a heavy-duty truck. Here, the platoon controller has a two-layer structure, with a low-level controller to regulate the vehicle acceleration (which is a challenging task, compared with passenger vehicles) and a high-level vehicle-following controller, which is vehicle independent, to a certain extent. Suffering from the same gear-shift problem as the previous team, however, it is concluded that smooth behavior at large distance errors must explicitly be taken into account in the controller design, e.g., by implementing a desired headway time that depends on the distance error.

"Cooperative Adaptive Cruise Control Implementation of Team Mekar at the Grand Cooperative Driving Challenge" by L. Güvenç, I. M. C. Uygan, K. Kahraman, R. Karaahmetoglu, I. Altay, M. Sentürk, M. T. Emirler, A. E. H. Karci, B. A. Güvenç, E. Altug, M. C. Turan, Ö. S. Tas, E. Bozkurt, Ü. Özgüner, K. Redmill, A. Kurt, B. Efendioglu

The Mekar team, with members from Istanbul Okan University, Istanbul Technical University, and Istanbul Arel University,

essentially applied the same platoon control strategy as the ATeam but implemented it on a compact car instead. Their vehicle platform, however, was not originally equipped with an ACC, and as a result, much effort had to be spent on the low-level (acceleration) controller during the GCDC competitions. As far as high-level (CACC) control is concerned, it is acknowledged, as in many other contributions, that graceful degradation mechanisms play a key role in the deployment of real-time cooperative driving systems in general and CACC in particular.

CONCLUSION

The 2011 GCDC competition successfully showed automated cooperative vehicle following in a multivendor setting, with teams from different countries and vehicles from different brands, ranging from a compact vehicle to a heavy-duty truck, and various control system designs. In addition, evaluating various solutions in the context of a challenge was generally perceived to be very useful, allowing for very direct interaction among different research groups.

Several issues have been identified that should be addressed in future challenges, one of the most important being the ability to cope with flawed or missing data from other vehicles. This is a prerequisite for the implementation of fault tolerance and graceful degradation. Furthermore, future challenges should also incorporate lateral aspects such as merging and splitting to move toward realistic solutions. It is expected that, for more advanced tasks like these, the need will arise for negotiation protocols that enable the vehicles to agree on which actions are to be performed.

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REFERENCES

[1] J. VanderWerf, S. E. Shladover, M. A. Miller, and N. Kourjanskaia, "Effects of adaptive cruise control systems on highway traffic flow capacity," *Transp. Res. Rec.*, vol. 1800, no. 1, pp. 78–84, 2002.

[2] B. van Arem, C. J. G. 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.

[3] W. S. Levine and M. Athans, "On the optimal error regulation of a string of moving vehicles," *IEEE Trans. Autom. Control*, vol. 11, no. 3, pp. 355–361, Jul. 1966.

[4] S. Sheikholeslam and C. A. Desoer, "Longitudinal control of a platoon of vehicles with no communication of lead vehicle information: A system level study," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, pp. 546–554, Nov. 1993.

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

[6] A. Vahidi and A. Eskandarian, "Research advances in intelligent collision avoidance and adaptive cruise control," *IEEE Trans. Intell. Transp. Syst.*, vol. 4, no. 3, pp. 143–153, Sep. 2003.

[7] E. Shaw and J. K. Hedrick, "String stability analysis for heterogeneous vehicle strings," in *Proc. Amer. Control Conf.*, New York, Jul. 11–13, 2007, pp. 3118–3125.

[8] 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.

[9] S. E. Shladover, C. Nowakowski, D. Cody, and J. O'Connell, "Cooperative adaptive cruise control: Field testing of driver use and acceptance," in *Proc. 16th World Congr. Exhib. Intell. Transp. Syst. Serv.*, Stockholm, Sweden, Sep. 21–25, 2009.

[10] I. Kulp, Comesafety's contribution to standardisation, Jul. 2008. [Online]. Available: http://www.cvisproject.org/download/Pressarticles2008/COMeSafety_Newsletter_Issue-5.pdf

[11] R. Brignolo, C. Zott, A. Spence, A. Brakemeier, G. Vivo, F. Bonnefoi, A. K. Mokaddem, L. Andreone, S. Cosenza, S. Zangherati, G. Zennaro, F. Visintainer, R. Schubert, and C. Bartels, Description of the integrated vehicle and infrastructure platform. SAFESPOT Deliverable D8.4.2, Apr. 2008. [Online]. Available: http://www.safespot-eu.org/documents/D8.4.2_Integrated_vehicle_Infrastructure_Platforms.pdf

[12] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[13] R. Hekmat, *Ad-hoc Networks: Fundamental Properties and Network Topologies*. Dordrecht, The Netherlands: Springer-Verlag, 2006.

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