Guest Editorial Introduction to the Special Issue on the 2016 Grand Cooperative Driving Challenge

I. INTRODUCTION

C OOPERATIVE driving is based on wireless communications between vehicles and between vehicles and roadside infrastructure, aiming for increased traffic flow and traffic safety, while decreasing fuel consumption and emissions. To support and accelerate the introduction of cooperative vehicles in everyday traffic, in 2011, nine international teams joined the Grand Cooperative Driving Challenge (GCDC). The challenge was to perform platooning, in which vehicles drive in road trains with short intervehicle distances. The results were reported in a Special Issue of IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS, published in September 2012 [item 1 in the Appendix].

Since then, cooperative vehicles have gained increasing interest on a global scale, in the scientific community as well as in industry-driven implementation-oriented projects. Here, cooperative applications often aim to support the driver, building on collaboration through wireless exchange of information, but do not necessarily include vehicle automation. In parallel, car makers are continuously adding new automation features to support safety and to increase passenger comfort, ultimately aiming for autonomous automated vehicles, i.e., highly automated vehicles with the ability to drive with the support of on-board proximity sensors only, thus excluding wireless information exchange. The integration of cooperative driving and automated driving is to be expected, resulting in cooperative automated driving (CAD), which is an important part of the broader area known as cooperative intelligent transportation systems (ITS).

With the aim to showcase CAD as part of cooperative ITS and accelerate its deployment in real-life traffic, the i-GAME project [item 2 in the Appendix], funded by the European 7th Framework Programme, was started in 2013. This project culminated in a second version of the GCDC, which was held in May 2016. The GCDC 2016 aimed to take CAD a step further by integrating interoperable wireless communications and advanced maneuvers, coordinated through interaction protocols [item 3 in the Appendix] and executed by means of automated longitudinal and lateral vehicle control. To this end, two cooperative yet competitive scenarios were defined, being automated lateral merging of two vehicle platoons on a highway and automated crossing of three vehicles at an

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TITS.2018.2815103

Fig. 1. A still of the GCDC highway merging scenario.



Fig. 2. A still of the GCDC intersection crossing scenario.

intersection without traffic signals; see Fig. 1 and Fig. 2, respectively, for an impression of those scenarios. Focusing on the multi-vendor implementation and interoperability, as well as on close-to-reality scenarios, the challenge provided an environment to showcase the latest advancements on cooperative automated vehicles.

Ten university teams participated in the GCDC 2016, leading to ten different approaches to execute the scenarios, using a variety of control solutions, system architectures, software/hardware implementations, and vehicle platforms. As such, a comprehensive overview was obtained regarding solutions for automated maneuvering in the scope of CAD, which were all evaluated in practice. The objective of this Special Issue is to present these solutions, thereby providing new technical and scientific insights into cooperative vehicle automation.

1524-9050 © 2018 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

II. SCANNING THE SPECIAL ISSUE

This Special Issue contains the contributions of eight of the GCDC teams. Each paper is briefly introduced below, starting with an introductory paper about the technical aspects of the challenge itself. Note that the participant papers are listed in the order of the final team ranking in the 2016 GCDC.

Cooperative Automated Maneuvering at the 2016 Grand Cooperative Driving Challenge

J. Ploeg et al.

This paper serves as an introduction to the Special Issue, describing the challenge scenarios, the interaction protocols that define the wireless message exchange to initiate the required vehicle maneuvers, the judgment criteria, and the safety aspects of the challenge. Moreover, the control solutions as implemented in the so-called *benchmark vehicles* are described. In addition, a wireless communication message set is presented to execute the scenario maneuvers, indicating that the currently available standardized ITS G5 message sets do not support cooperative maneuvers to a sufficient extent.

An Approach for Receiver-Side Awareness Control in Vehicular Ad Hoc Networks

V. Díez Rodrígues et al.

Vehicular ad hoc networks are a key element of cooperative ITS. Also in the GCDC, wireless communications played a crucial role in implementing the interaction protocols required for joint execution of the scenario maneuvers. Consequently, message congestion may compromise the cooperation of the vehicles engaged in the scenario. To counteract message congestion, this contribution of the winning team from Halmstad University, Sweden, proposes a novel buffering system on the receiver side by means of prioritizing and discarding messages, based on the relevance of the transmitting vehicle and the message content.

Modelling the Level of Trust in a Cooperative Automated Vehicle Control System

T. Rosenstatter and C. Englund

In a cooperative setting, each vehicle has to make decisions about its actions as part of the interaction protocol, among others based on communicated information. This second paper from the Halmstad University team explores uncertainty of the information required for decision making, causing the latter to be a probabilistic rather than a deterministic process. A socalled trust index is introduced, indicating the level of trust in the environment, the ego vehicle, and the surrounding vehicles. By means of the platoon merge scenario, it is illustrated how this trust index enhances decision making in terms of reliability and safety.

Team Halmstad Approach to Cooperative Driving in the Grand Cooperative Driving Challenge 2016

M. Aramrattana et al.

The third contribution to this Special Issue of the Halmstad University team presents the overall automation

system architecture and software modules of their vehicle. In particular, the application of the new wireless message buffering system is illustrated, as explained in more detail in their first paper, as well as the trust system approach, explained in their second paper. Furthermore, it is stressed that considerable effort was put into enhancing the reliability of the automation system, which arguably led to winning the GCDC.

Making Bertha Cooperate—Team AnnieWAY's Entry to the 2016 Grand Cooperative Driving Challenge

Ö. Ş. Taş et al.

This contribution, from Karlsruhe Institute of Technology, Germany, presents a comprehensive overview of the vehicle system architecture and the software modules. In particular, focus is put on yet another important aspect of cooperative maneuvering: A motion planner is introduced that is capable of planning different maneuvers flexibly by augmenting the cost function with situation-specific cost terms, while including information obtained through wireless communications. Moreover, it is emphasized that interaction protocols should be designed to avoid a single point-offailure, potentially causing the entire maneuver execution to fail.

Development of Platform-Independent System for Cooperative Automated Driving Evaluated in GCDC 2016 *S. Kokogias et al.*

KTH, Sweden, presents a vehicle system architecture for CAD, which is implemented on two conceptually different vehicles, i.e., a truck and a four-wheel-steered concept vehicle. Although similar components as in the previous paper are present, obviously, this architecture explicitly identifies a supervisory controller, which is responsible for handling the interaction protocol. Consequently, a hierarchical architecture arises, consisting of a decision-making layer and a maneuver-execution layer. In addition, decoding congestion of the wireless messages is addressed by means of estimating future message load and probabilistically discarding received messages in the case of overload, thus putting forward an alternative solution to the one proposed by the Halmstad team.

Design and Experimental Validation of a Cooperative Driving Control Architecture for the Grand Cooperative Driving Challenge 2016

R. Hult et al.

This paper from the Chalmers Car team, Chalmers University, Sweden, also focuses on the in-vehicle system architecture. This architecture is similar to the ones mentioned before, but here the decision-making unit, which implements the interaction protocols, has been explained in detail. In particular, it is concluded that the interaction protocol may significantly increase complexity of the controller design. This, in fact, touches upon the issue of scalability of the control system in case of a large number of scenarios and associated interaction protocols.

The Best Rated Human–Machine Interface Design for Autonomous Vehicles in the 2016 Grand Cooperative Driving Challenge

O. Benderius et al.

Increasing levels of vehicle automation require new humanmachine interface (HMI) designs, which is why, in the GCDC, the HMI design of all teams was assessed by experts. In this paper by the Chalmers Truck team, whose HMI design was rated as the best, it is argued that with increasing automation levels, the HMI should be designed according to a *show, don't tell* principle, visually indicating the vehicle's safety state and intentions. Moreover, the HMI should focus on the occupants of the vehicle as well as other humans that may interact with the system. Therefore, both an internal and an external interface are presented.

Cooperative Automated Driving for Various Traffic Scenarios: Experimental Validation in the GCDC 2016

V. Dolk et al.

Next to the system architecture and the perception system design, the paper of the ATeam from Eindhoven University of Technology and Fontys University of Applied Sciences, The Netherlands, addresses network imperfections such as packet loss by presenting a relationship between the maximum allowable transmission interval and the maximum allowable communication delay. These notions from the field of networked control are particularly relevant if event-triggered instead of time-triggered communication is implemented. The latter was still adopted in the GCDC, but event-based communication is a promising technique to efficiently use the limited bandwith.

The Experience of DRIVERTIVE—DRIVERless cooperaTive VEhicle—Team in the 2016 GCDC

I. Parra Alonso et al.

The DRIVERTIVE team from University of Alcalá, Spain, performed very well in the competition, but suffered from hardware failures at some point, due to which they could not complete all competition scenarios. Their contribution to this Special Issue focuses in part on the steer angle and speed control of the vehicle, providing ample insight into the challenges associated with lower-level vehicle controller design, among which are nonlinear driveline behavior and input saturation. This, in fact, illustrates that "high-level" performance starts with a well-designed low-level control system.

III. CONCLUSION

The 2016 GCDC has shown that it is feasible to jointly execute complex traffic scenarios among road vehicles of different make and with different automation systems, provided that a well-defined interaction protocol exists, describing the wireless message exchange that initiates the required vehicle maneuvers. As such, this result is in line with the expectation that was formulated at the completion of the 2011 GCDC.

Many topics that are relevant for cooperative automated driving have been addressed in this Special Issue, among which are system architecture, environmental perception and sensor fusion, controller design, and HMI design. In particular, ample attention is paid to the various aspects of wireless communications, such as assignment of a trust level, measures against message congestion, and quantification of the allowable communication delay.

The interaction protocol as defined by the GCDC organization also received much attention. From this, it can be concluded that resilience of this protocol to potential failures of vehicles that participate in the scenario is of crucial importance. Furthermore, implementation of this interaction protocol requires a supervisory control layer, which could also be observed in the automation system architecture as described by multiple contributions to this Special Issue. A topic that was not touched upon yet, but will need to be addressed in the near future, is the scalability of the supervisory controller design, which becomes relevant with an increasing number of cooperative scenarios to be implemented.

In summary, the GCDC represented a significant step forward in the field of CAD, but there are still important scientific and technical challenges to overcome before CAD can be put into practice. Among these challenges is not only the development of a scalable supervisory control layer implementing robust interaction protocols, as already mentioned, but also robustness against non-equipped (manually driven) vehicles and road safety in the presence of failures of the in-vehicle automation systems.

> JEROEN PLOEG, Guest Editor CRISTOFER ENGLUND, Guest Editor HENK NIJMEIJER, Guest Editor ELHAM SEMSAR-KAZEROONI, Guest Editor STEVEN E. SHLADOVER, Guest Editor ALEXEY VORONOV, Guest Editor NATHAN VAN DE WOUW, Guest Editor

APPENDIX

RELATED WORK

- J. Ploeg, S. Shladover, H. Nijmeijer, and N. van de Wouw, "Introduction to the special issue on the 2011 Grand Cooperative Driving Challenge," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 989–993, Sep. 2012.
- Interoperable GCDC AutoMation Experience (i-GAME) Project. Accessed: Jan. 8, 2018. [Online]. Available: http://www.gcdc.net/en/igame
- E. Semsar-Kazerooni and J. Ploeg, "Interaction protocols for cooperative merging and lane reduction scenarios," in *Proc. IEEE 18th Int. Conf. Intell. Transp. Syst.*, Sep. 2015, pp. 1964–1970.



Jeroen Ploeg received the M.Sc. degree in mechanical engineering from Delft University of Technology, Delft, The Netherlands, in 1988 and the Ph.D. degree in mechanical engineering on the control of vehicle platoons from Eindhoven University of Technology, Eindhoven, The Netherlands, in 2014.

From 1989 to 1999, he was with Tata Steel, IJmuiden, The Netherlands, where his interest was in the development and implementation of dynamic process control systems for large-scale industrial plants. Since 1999, he has been with TNO, Helmond, The Netherlands, where he is currently a Principal Scientist. He is also a part-time Associate Professor with the Mechanical Engineering Department, Eindhoven University of Technology. His research interests include control system design for cooperative and automated vehicles, in particular string stability of vehicle platoons, the design of interaction protocols for complex driving scenarios, and motion control of wheeled mobile robots.

Cristofer Englund received the Ph.D. degree in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden, in 2007.

He currently holds a research managerial position within cooperative systems with RISE Viktoria, Gothenburg. He is also the Research Director of the traffic systems competence area with SAFER, Vehicle and Traffic Safety Centre, Chalmers University of Technology. He also holds an adjunct senior lecturer position with Halmstad University within information technology. His research interests include automated driving, machine learning, and data mining.



Henk Nijmeijer (F'00) received the M.Sc. and Ph.D. degrees in mathematics from University of Groningen, Groningen, The Netherlands, in 1979 and 1983, respectively.

From 1983 to 2000, he was with the Department of Applied Mathematics, University of Twente, Enschede, The Netherlands. Since 2000, he has been a Full Professor with the Dynamics and Control Group, Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands. He has authored a large number of journal and conference papers, and several books. Since 2011, he has been an IFAC Council Member and, since 2015, he has been the Scientific Director of the Dutch Institute of Systems and Control.

Dr. Nijmeijer is an Editor of *Communications in Nonlinear Science and Numerical Simulations*. He was a recipient of the IET Heaviside Premium in 1990 and, in 2011, he was appointed as an Honorary Knight of the Golden Feedback Loop at the Norwegian University of Science and Technology. In 2015, he was a recipient of the IEEE Control Systems Technology Award.



Elham Semsar-Kazerooni received the Ph.D. degree in electrical engineering from Concordia University, Montreal, Canada, in 2009.

She was an FQRNT Post-Doctoral Fellow with University of Toronto, Toronto, Canada, from 2010 to 2012. She is currently a Senior Scientist with the Automotive Department, TNO, Helmond, The Netherlands. She also has a part-time affiliation with the Group of Hybrid Systems, Department of Applied Mathematics, Twente University, Enschede, The Netherlands. She authored the book *Team Cooperation in a Network of Multi-Vehicle Unmanned Systems: Synthesis of Consensus Algorithms* (Springer-Verlag, 2012), with K. Khorasani. Her research interests include cooperative control systems, control of vehicle platoons, interaction protocols for cooperative driving, consensus seeking theory, nonlinear systems analysis, and optimal system design.



Steven E. Shladover received the B.S., M.S., and D.Sc. degrees in mechanical engineering with a specialization in dynamic systems and control from Massachusetts Institute of Technology, Cambridge, USA. He began conducting research on vehicle automation at Massachusetts Institute of Technology in 1973.

He was with Systems Control, Inc., and Systems Control Technology, Inc., for eleven years, where he led the company's efforts in transportation systems engineering and computer-aided control engineering software products. He joined the PATH Program in 1989. He recently retired from his position as the Program Manager of Mobility with the California PATH Program, Institute of Transportation Studies, University of California at Berkeley, Berkeley, CA, USA.

Dr. Shladover has been active in the American Society of Mechanical Engineers as the former Chairman of the Dynamic Systems and Control Division, Society of Automotive Engineers ITS Division, and the Transportation Research Board as the Chairman of the Committee on Intelligent Transportation Systems from 2004 to 2010 and as a member of the Committee on

Vehicle-Highway Automation from its founding until 2010 and has been the Chairman since 2013. He also was the Chairman of the Advanced Vehicle Control and Safety Systems Committee of the Intelligent Transportation Society of America from its founding in 1991 until 1997. He leads the U.S. delegation to ISO/TC204/WG14, which is developing international standards for vehicle-roadway warning and control systems.



Alexey Voronov received the M.Sc. and Ph.D. degrees from Chalmers University of Technology, Gothenburg, Sweden, in 2007 and 2013, respectively.

He is currently a Senior Researcher in cooperative systems with RISE Viktoria, Gothenburg, Sweden. His research interests include applied computer science, complex systems, and intelligent transportation solutions.



Nathan van de Wouw received the M.Sc. (Hons.) and Ph.D. degrees in mechanical engineering from Eindhoven University of Technology, Eindhoven, The Netherlands, in 1994 and 1999, respectively.

In 2000, he was with Philips Applied Technologies, Eindhoven, and in 2001, he was with The Netherlands Organisation for Applied Scientific Research TNO, Delft, The Netherlands. He held positions as a Visiting Professor with the University of California at Santa Barbara, CA, USA, from 2006 to 2007, University of Melbourne, Melbourne, Australia, from 2009 to 2010, and University of Minnesota, Minneapolis, MN, USA, from 2012 to 2013. He currently holds a full professor position with the Mechanical Engineering Department, Eindhoven University of Technology. He also holds an adjunct full professor position with University of Minnesota and a part-time full professor position with Delft University of Technology, Delft. He has authored a large number of journal and conference papers and the books *Uniform Output Regulation of Nonlinear Systems: A Convergent Dynamics Approach* (Birkhauser, 2005),

with A. V. Pavlov and H. Nijmeijer, and *Stability and Convergence of Mechanical Systems with Unilateral Constraints* (Springer-Verlag, 2008), with R. I. Leine.

His current research interests are the modeling, analysis, and control of nonlinear/hybrid systems, with applications to vehicular platooning, high-tech systems, resource exploration, smart energy systems, and networked control systems. In 2015, he received the IEEE Control Systems Technology Award for the development and application of variable-gain control techniques for high-performance motion systems. He is currently an Associate Editor of *Automatica* and IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY.