Guest Editorial
Multifaceted Driver–Vehicle Systems: Toward More Effective Driving Simulations, Reliable Driver Modeling, and Increased Trust and Safety

THE current panorama of driver–vehicle systems is rapidly evolving, as the path toward autonomous vehicles is being paved. Many design decisions are yet to be made, and evolving legislative policies will play a significant role in the scientific research, which needs to be addressed. For example, there are countries that are considering a "step change" from fully human- driven to fully automated vehicles, while others are designing a period of coexistence of the two driving modes. Clearly, either of these approaches will require deep study of the interactions that will develop between drivers and vehicles. Related to this, for the first time in history, automated systems will primarily control vehicles and drivers may become passive "spectators" to vehicle control. However, it is also reasonable to expect that humans will be asked to intervene in dubious and/or dangerous situations that are not manageable by automation alone. Such interventions may also be used as bases for "robotic drivers" to learn human-based reasoning and ethics in vehicle control. Some researchers have already started to ask for how long will "former" drivers be able to offer prompt and wise reactions to off-nominal events, as their capabilities will decline with automation dependence and loss of practice.

It is easy to foresee that the next decade will be crucial for scientific research in this field. Scientists will be asked to provide prompt and reliable responses to whatever final human–automation interaction scenario will develop for driving activities. To address this need, human–machine systems competencies will be of the utmost importance.

In the context outlined above, and in preparation for autonomous vehicles driving around the world, some of the issues that need to be tackled include design of more accurate and reliable driving simulation models for coexistence tests, in which autonomous vehicles are simulated together with human-driven ones. Such technology is needed to reproduce interaction schemes that will develop on roadways and replicate the specific cues to which drivers may be exposed for the assessment of consequent behaviors. These tools are expected to provide more efficient methods for estimating different aspects of driver behaviors (possibly to form a knowledge base for autonomous vehicle systems programming for decision making in mixed technology environments). Finally, simulations can be used for training to build bonds of trust among different roadway actors, in order to facilitate a smoother transition between mixed-mode traffic and completely autonomous traffic.

Within this challenging context, this special issue (SI) was conceived to bring together recent and innovative views on the aforementioned emerging topics. The majority of the papers selected to appear in this SI have already appeared online through the IEEE Xplore system, and several papers have already attracted significant attention, having many full-text views.

After the evaluation of the final accepted papers that met the production deadlines, ten works were selected to appear in this SI. The papers address all the emerging aspects of driver–vehicle systems that have been identified above. Eight of these are regular papers and two are technical correspondences, which appear at the end of the issue.

As an overview of the SI, the papers are organized to allow the reader to begin by considering works that focus on different aspects of simulator and virtual reality tools [items 1)–3) in the Appendix] and then move to studies related to different aspects of driver modeling, based on various types of human and vehicle control measurements [items 4)–6) in the Appendix]. Items 7)–10) in the Appendix move the focus to more complex interactions between drivers, vehicles, and their automated features, with special reference to safety and trust. In this context, in [items 7) and 8) in the Appendix], systems are analyzed to ensure safety at intersections and in overtaking maneuvers, whereas in [item 9) in the Appendix], a design paradigm for driver—vehicle human–machine interfaces (HMIs) is proposed to promote the creation of trust in the automated vehicle features. Finally, the technical correspondence [item 10) in the Appendix] discusses how to improve quantitative indexes to detect and evaluate the risk of rear-end collisions. Being able to detect and monitor possible accidents, and to do so robustly and reliably in an automatic fashion is another important ingredient in promoting trust in future roadway scenarios, in which human and automated drivers will have to interact. Thus, a multifaceted view of driver–vehicle systems is explored in the SI, providing the reader with the most recent views on some of the most important topics in defining this complex and ever-evolving interaction. Our general hope is that such a consistent and structured discussion of open problems and recent solutions in this field might provide a strong basis on which new research and new findings can be built. Coexistence of human drivers with semi-autonomous features is already an on-going real-world experi-

Digital Object Identifier 10.1109/THMS.2017.2784018

ment! Even with low-level autonomy, many cars already have adaptive cruise control (including stop and go), autonomous parking capability, full braking for collision avoidance, etc. All such systems are examples of semiautonomous driving and show a very relevant market penetration rate, which is bound to exponentially grow. To correctly manage this growth, the research efforts in this field must converge to provide solid and real-life solutions.

In the rest of this editorial, the contributions of the SI are briefly presented and discussed. First, the contributions dealing with simulator design and virtual reality frameworks are introduced. Driving simulators are nowadays a common tool and are widespread in use at an industrial level, for performing preliminary validation of algorithms for safety and assistance systems. In automated driving scenarios, simulation is even more important, as experimental tests are difficult to carry out and can be performed only once a control system under has been demonstrated to be robust and reliable. Item 1) in the Appendix offers a solution to improve the motion control strategies used for generating both realistic and feasible inputs for drivers. This is a task of the so-called "Motion Cueing Algorithm" (MCA). A relevant part of the effectiveness of such devices relies on the capability of motion action to provide drivers with the most reliable driving sensations while maintaining the platform within its operational space. In the present paper, a model predictive control based MCA with look-ahead strategy is proposed. The MCA is intended to achieve an optimal balance between the system objectives of harmonizing actual driver actions with expected actions and to maximize work-space usage while being robust to unexpected driver actions.

Another important issue related to MCA is the use of mapping inertial vehicle motion onto limited simulator motion space. This mapping causes mismatches between the unrestricted visual motion and the constrained inertial motion, which results in perceived motion incongruence (PMI). It is still largely unknown what exactly causes visual and inertial motion in a simulator to be perceived as incongruent by a human observer. Item 2) in the Appendix addresses this interesting and relevant issue by proposing a way to quantify the PMI in a time-varying manner. Time variance, which is the key novel ingredient of the new method, allows for differential weighting of the incongruence according to the time duration of sensation and for better assessment of time-varying short-duration motion mismatches. The validation of the approach is carried out by analyzing the results of a human-in-the-loop experiment, where continuous rating of PMI was performed in a motion-based simulator during a passive driving simulation.

Another important issue in the simulation context is designing and developing virtual environments that realistically represent the range of different human—automated vehicle interaction patterns. This involves replicating not only the technical features of the systems, but also the feelings that drivers experience in actual vehicle control. As such, the fidelity of the virtual environment must provide confidence that there is replication of perceptions occurring in real-world experiences. To do this, significant computational power is needed, and related performance limits put in place a tradeoff between such computational power and the overall fidelity levels achieved. In [item 3) in the Appendix], an analysis of subjective perception of driver feelings using a virtual environment is assessed in an experiment involving 44 participants.

The experiment was undertaken in such a way that participants experienced a real-world driving scenario and were asked to judge the virtual equivalent of the real-world experience, where the virtual setting was designed to offer three different levels of graphic quality, low, medium, and high. The study shows that the "low" quality was easily recognized, whereas no real separation between "medium" and "high" levels was perceived. This gives an important direction in this type of research, saying that computational power can be saved by focusing on a medium-level graphic definition, and otherwise, improve other simulation characteristics.

As mentioned before, a key issue to move toward autonomous vehicles and automated roads is to carefully model human driver behaviors. Such modeling is aimed at understanding the key features leading to driving decisions and patterns of behavior. The objectives of this line of research are twofold: 1) Models of driver behaviors can be used to support autonomous vehicle control in mixed-mode traffic situations when an autonomous vehicle meets a human-driven one and can project common driver behaviors that may take place; and 2) models may be used as a basis for causing autonomous vehicles to replicate human driving behavior, so that they also become predictable for human drivers when they meet them on the road. Along these lines, [item 4) in the Appendix] establishes an objective method for evaluating driver steering comfort, which includes both posture comfort and operational comfort. Most studies of posture comfort primarily focus on the angle ranges of body joints for comfortable driving posture and subjective measures that can be time-consuming and expensive to collect and are subject to individual biases. The researchers propose the use of electromyography (EMG) and movement trajectories of driver upper limbs during steering maneuvers to assess comfort. A total of 21 drivers completed a steering experiment where EMG and movement trajectories of the upper limbs were measured, together with their subjective evaluation of steering comfort. For analysis purposes, five evaluation indices, including EMG and movement information, were defined based on the measurements from the initial study. Correlation analyses indicted a relationship between each of the evaluation indices and steering comfort rating. These results indicate feasibility in establishing an objective evaluation approach for vehicle steering comfort.

The study of brain–machine interface systems has grown dramatically over the past two decades, and many are seeking ways to address driver fatigue issues by using unobtrusive brain–machine interface systems. In [item 5) in the Appendix], a promising unobtrusive brain–machine interface system for detecting driver drowsiness is designed and implemented. The proposed system goals include: 1) simultaneous electroencephalography (EEG) and gyroscope-based head movement measurement for early detection of driver drowsiness, and 2) simultaneous EEG and transcranial direct current stimulation for the early management of driver drowsiness. This system was realized using bluetooth technology that can communicate with a smartwatch, which coordinates the work of drowsiness monitoring and brain stimulation with its embedded closed-loop algorithm. Experimental results show that the proposed system obtained a 93.67% five-level overall classification accuracy, a 96.15% two-level (alert versus slightly drowsy) accuracy, and maximum 16–23 min wakefulness maintenance.

Item 6) in the Appendix seeks to develop a new model to detect risky driving behaviors based on vehicle speed time series collected through a GPS unit. The researchers tested two primary assumptions.

1) The speed records of risky drivers tend to have larger acceleration rates than those of normal drivers; and 2) the speed records of risky drivers tend to have more frequent acceleration and deceleration movements than those of normal drivers. The researchers adopted a naturalistic driving method to model individual differences in driving patterns. Applying a K-means cluster analysis to partition speed ranges and designing separate identification models for each speed range assisted in detecting individual differences. Through this model, the team found that normal and risky drivers have different distribution patterns of positive speed-change (value and duration) tuples, and these patterns could be used to identify risky drivers.

Item 7) in the Appendix represents another approach to driver–vehicle interaction modeling. In particular, the authors introduce a "supervisor" that increases safety at traffic intersections by enhancing human-determined maneuvers. By incorporating human intent in the supervisor modeling solution, the authors expected to realize an improved user experience in relation to corrective control actions made by the supervisor, as opposed to supervisors that ignore a driver's will. Since optimal algorithms are computationally complex, this paper also features an approximate solution that can solve the supervisor problem in polynomial time with bounded running time and error, also showing good performance.

With the proliferation of autonomous capabilities in our vehicles, new challenges appear that are not only related to vehicle control, but also concern human factors. One crucial aspect for the success of autonomous and semiautonomous driving is the need for drivers to trust automated vehicles. Following this approach, in [item 8) in the Appendix], a driving simulator is used to investigate trust in a scenario in which a car performs automated overtaking of a scooter and a bicycle. The authors find that driver trust varies depending on lateral and longitudinal safety distances of automated control responses, along with the peak overtaking speed. Results show that if we aim to build a more solid bonding trust between drivers and their automated cars, automated responses need to be adapted to engage earlier in overtaking steering maneuvers, maintain greater lateral safety distances, and maintain a human-like overtaking speed. However, readers should consider that this study evaluates trust over very short periods of time. Longer exposures to automated maneuvers may influence the perception of drivers with regard to proper overtaking speed and safety distances.

Related to [items 8) in the Appendix], [9) in the Appendix] clearly shows that trust is a dynamic process. This latter item presents a practical method that helps to create a proper level of driver trust in automated driving by taking a holistic perspective on the implementation of an automated driving HMI. To achieve the HMI, trust-related factors are identified for each phase of the human–vehicle experience, including events before and after the actual interaction between the driver and the vehicle. The authors also include guidelines on how to use these factors to create the proper amount of trust. However, readers should not expect to find a complete manual on how to design an HMI. Instead, designers and interested practitioners will find in this paper a useful guide for the HMI implementation. Likewise, the authors remind us that since the perception of trust varies with time, the HMI implementation should also be able to adapt over time.

The last paper of this SI [item 10) in the Appendix] represents a step forward to support in addressing the problem of read-end collision risk. In particular, within the frame of a forward obstacle collision warning system (FCWS), the authors propose an algorithm that considers the acceleration of the following vehicle to estimate the deceleration needed for a driver's vehicle in order to ensure collision avoidance. Similarly, stimulus–response experiments using a driving simulator allow the authors to identify proper reaction latency times that are incorporated into their system. Numerical experiments performed with a limited dataset show that this solution outperforms conventional FCWS systems.

M. TANELLI, *Guest Editor*
Dipartimento di Elettronica
Informazione e Bioingegneria
Politecnico di Milano
Milano 20133, Italy

R. TOLEDO-MOREO, *Guest Editor*
Dipartimento de Electrónica y Tecnología de Computadoras
Universidad Politécnica de Cartagena
Cartagena 30202, Spain

L. M. STANLEY, *Guest Editor*
Department of Industrial Engineering
Clemson University
Clemson, SC 29634, USA

ACKNOWLEDGMENT

The guest editors would like to thank all the authors and the anonymous reviewers for their fundamental contributions to this special issue. They would also like to thank Prof. D. Kaber, current Editor-in-Chief of the IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS, for giving them the opportunity of editing this issue, and for the dedication and competence with which he followed them throughout the work, and also C. Balejcsik for her help in the production process.

APPENDIX
RELATED WORK

1) M. Bruschetta, C. Cenedese, A. Beghi, and F. Maran, "A motion cueing algorithm with look-ahead and driver characterization: Application to vertical car dynamics," *IEEE Trans. Human-Mach. Syst.*, to be published.

2) D. Cleij, J. Venrooij, P. Pretto, D. M. Pool, M. Mulder, and H. H. Bu¨lthoff, "Continuous subjective rating of perceived motion incongruence during driving simulation," *IEEE Trans. Human-Mach. Syst*., to be published.
3) K. Debattista, T. Bashford-Rogers, C. Harvey, B. Waterfield, and A. Chalmers, "Subjective evaluation of high-fidelity virtual environments for driving simulations," *IEEE Trans. Human-Mach. Syst*., to be published.
4) G. Li and W. Y. Chung, "Combined EEG-gyroscope-tDCS brain machine interface system for early management of driver drowsiness," *IEEE Trans. Human-Mach. Syst*., to be published.
5) Y. Liu, Q. Liu, C. Lv, M. Zheng, and X. Ji, "A study on objective evaluation of vehicle steering comfort based on driver's electromyogram and movement trajectory," *IEEE Trans. Human-Mach. Syst*., to be published.
6) D. Wang, X. Pei, L. Li, and D. Yao, "Risky driver recognition based on vehicle speed time series," *IEEE Trans. Human-Mach. Syst*., to be published.
7) G. Rodrigues de Campos, F. Della Rossa, and A. Colombo, "Safety verification methods for human-driven vehicles at traffic intersections: optimal driver-adaptive supervisory control," *IEEE Trans. Human-Mach. Syst*., to be published.
8) G. Abe, K. Sato, and M. Itoh, "Driver trust in automated driving systems: The case of overtaking and passing," *IEEE Trans. Human-Mach. Syst*., to be published.
9) F. Ekman, M. Johansson, and J. Sochor, "Creating appropriate trust in automated vehicle systems: A framework for HMI design," *IEEE Trans. Human- Mach. Syst*., to be published.
10) T. Hiraoka and S. Takada, "Improvement of evaluation indices for rear-end collision risk," *IEEE Trans. Human-Mach. Syst*., to be published.

Mara Tanelli (M'05–SM'12) received the Laurea degree in computer engineering from the Politecnico di Milano, Milan, Italy, in 2003, the M.Sc. degree in computer science from the University of Illinois at Chicago, Chicago, IL, USA, in 2003, and the Ph.D. degree (*cum laude*) in information engineering from the Politecnico di Milano, Milan, Italy, in 2007.

She is currently an Associate Professor of automatic control with the Dipartimento di Elettronica, Informazione e Biongegneria, Politecnico di Milano. She is the coauthor and coeditor of 2 international books, more than 100 peer-reviewed publications, and national and international patents. Her current research interests include control systems design for vehicles, insurance telematics, classification and learning for control and sliding-mode and variable structure control.

Dr. Tanelli was the recipient of the 2008 Rudolf Kalman Best Paper Award from the *ASME Journal of Dynamic Systems, Measurements and Control*, the 2010 Control Engineering Practice Best Paper Prize, and the 2014 Best Young Author Paper Award from the Italian Chapter of the IEEE Control Systems Society. She is a member of the Conference Editorial Board of the IEEE Control Systems Society, and an Associate Editor for the IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY and the IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS. She has been in the IPC of several international conferences.

Rafael Toledo-Moreo received the M.S. degree in automation and electronics engineering from the Technical University of Cartagena (UPCT), Cartagena, Spain, in 2002, and the Ph.D. degree in computer science from the University of Murcia, Murcia, Spain, in 2006.

Between 2008 and 2010, he worked for one year with the Laboratoire Central des Ponts et Chausses (currently IFSTTAR), Nantes, France, and was also a Guest Researcher with the University of Paris South XI, France. He is currently an Associate Professor with the Department of Electronics and Computer Technology, UPCT, the Deputy Director of the International and Corporate Affairs of the School of Telecommunication Engineering, and the Head of the Telefonica Chair at UPCT. He has participated in almost 40 public and private research projects, being responsible of a global budget over 4 MEuros. He is the Principal Investigator of the infrared instrument control unit of the Euclid mission, an m-class cosmological mission of European Space Agency. His main research interests include space electronics and intelligent transportation systems.

Dr. Toledo-Moreo is currently an Associate Editor for the IEEE INTELLIGENT TRANSPORTATION SYSTEMS MAGAZINE, the IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS, and the *Journal of Transportation Technologies*. He has been a member of International Program Committees of many international conferences, including the IEEE International Conference on System, Man and Cybernetics and the IEEE Intelligent Vehicles Symposium, among many others. He was the recipient of two international research awards.

Laura M. Stanley received the B.S. degree in industrial and systems engineering from Virginia Tech, Blacksburg, VA, USA, and the M.S. and Ph.D. degrees in industrial engineering from Montana State University, Bozeman, MT, USA.

She is currently an Associate Professor and a Graduate Program Coordinator with the Industrial Engineering Department, Clemson University, Clemson, SC, US. She recently served as the Program Director in the Directorate for Computer & Information Science & Engineering in the Cyber-Human Systems Program at the National Science Foundation. Her research interests include human factors engineering; biomechanics/ergonomics; human–computer interaction; human-centered design in engineering; driver behavior in transportation safety; virtual reality validity, training and assessment; and engineering education. She has authored/coauthored more than 60 peer-reviewed publications in these research areas.

Dr. Stanley served as an Associate Editor for the IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS, and *Human Factors and Ergonomics in Manufacturing & Service Industries*. She also serves on the scientific review committees for the *Journal of the American Academy of Pediatrics*, *Accident Analysis & Prevention Journal*, *American Society for Engineering Education*, *Journal of the Human Factors & Ergonomics Society*, and *Transportation Research Board*.