Introduction to the Special Issue on Applications and Systems for Collaborative Driving

TRAFFIC safety and efficiency are major objectives for Intelligent Transportation Systems (ITS) [item 1) in the Appendix], [item 2) in the Appendix]. A lot of research has been done on autonomous vehicles and Advanced Driver Assistance Systems, which exploit a variety of sensors in order to support the driver and/or autonomous driving (e.g., [item 3) in the Appendix]–[item 7) in the Appendix]).

Hosting a variety of onboard sensors such as camera, radar, and light detection and ranging (LiDAR) [item 8) in the Appendix], the vehicle itself has now become a sensor [item 9) in the Appendix]. The smart connected vehicle is able to process information and communicate to nearby vehicles or, through the V2X technologies [item 10) in the Appendix], to remote servers, according to the cloud computing and Internet of Things paradigms [item 11) in the Appendix]. This is the cooperative driving model, a hot area in transport system research, in which different vehicles automatically share information to achieve common goals [item 1) in the Appendix], [item 12) in the Appendix]. This model is cost effective [item 13) in the Appendix], particularly in high traffic density areas [item 14) in the Appendix].

For instance, [item 15) in the Appendix] proposed a cooperative system including several applications, such as adaptive cruise control with consumption optimization, an overtaking assistance system in single-lane roads, an assistance system in intersections with speed control during approximation maneuvers, and collision avoidance with evasive maneuvers. Manzinger *et al*. [item 16) in the Appendix] introduce a novel concept based on collaborative maneuver templates, to select cooperative driving strategies. Jia and Ngoduy [item 17) in the Appendix] designed a consensus-based controller for the cooperative driving system (CDS) considering (intelligent) traffic flow that consists of many platoons moving together. Behere *et al.* [item 18) in the Appendix] present a reference architecture and discuss how it can influence system design and implementation in automotive systems. The simulated system proposed by Eilbrecht and Stursberg [item 19) in the Appendix] discuss cooperatively resolving conflicts that arise between several fully autonomous, communicating vehicles in general onroad traffic scenarios. A novel cooperative conflict resolution scheme is proposed, which orchestrates the plans of neighboring vehicles, trying to minimize a common cost function.

To support the developments in cooperative driving toward deployment in realistic traffic, the second grand cooperative driving challenge (GCDC) took place in Helmond, The Netherlands, in 2016. IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS has provided excellent coverage of this initiative. Dolk *et al.* [item 20) in the Appendix] provide an overview of the ATeam's hardware and software implementation of the cooperative automated driving system for cooperative merging on a highway and cooperative intersection-crossing scenarios. Kokogias *et al.* [item 21) in the Appendix] describe the common system architecture for a platform-independent cooperative system. They also present a novel approach to trajectory-tracking control for a four-wheel steering vehicle using model predictive control. Benderius *et al.* [item 22) in the Appendix] provides an in-depth description of the best-rated human–machine interface that was presented during the 2016 GCDC. Parra *et al.* [item 23) in the Appendix] analyzed the performance of ITS-G5A communications for an autonomous driving application in a real high-density scenario, such as the one provided by GCDC.

Collaborative driving is a further, natural development, already pursued by some of the above papers, putting drivers and travelers in the center of the process, through participation, awareness, motivation, community building, and coaching (e.g., [item 24) in the Appendix]). With increased automation in vehicles, the cooperation between automated systems and human drivers becomes ever more important. Empirical studies on practical implementations of cooperative guidance and control show that cooperative guidance and control is not only theoretically appealing [item 25) in the Appendix]. Considering the transition toward autonomous vehicles, [item 26) in the Appendix] stresses the importance of human factors to deal with drivers' over-trust, lack of attention, and slow reaction times.

These factors have been the main motivations that drew the Guest Editors to propose to the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS readers this special issue, Applications and Systems for Collaborative Driving.

The call for paper attracted 26 manuscripts, of which only 7 have been selected for the special issue. Some of the other papers had a longer path and will appear as regular articles in upcoming issues of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS. The following is an overview of the selected papers.

"Integrating Intuitive Driver Models in Autonomous Planning for Interactive Maneuvers" by Govindarajan and Bajcsy assumes that autonomous vehicles will have to be capable of driving in a mixed environment, collaboratively

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with both humans and autonomous vehicles. In this situation, the behaviors of human-driven vehicles and their typical interactions in collaborative maneuvers must be modeled and understood in an accurate and precise manner. Then, integrating such models into autonomous planning can develop control frameworks that mimic this shared understanding. The authors present a driver modeling framework that estimates an empirical reachable set to capture typical lane-changing behaviors. Leveraging this driver model can generate trajectories similar to those performed by humans. Using this modeling and planning framework can improve understanding and integration of nuanced interactions to improve collaboration between humans and autonomy.

"Cooperative Adaptive Cruise Control (CACC) for String Stable Mixed Traffic: Benchmark and Human-Centered Design" by Li and Wang proposes novel criteria for the string stability of mixed (both automated and manual driving) vehicle platoons. With proper arrangements of the platoon sequence as well as mild restrictions on the leading car's velocity overshoot, the proposed mixed traffic string stability can be realized via some suitable controller design for the automated cars. The action-point car-following model is adopted to quantify the driver's psychological comfort in combination with the quantification of physical comfort based on jerk. On the other hand, a model predictive control-like blending ratio controller is developed to obtain the optimal time headway in the feedback controller for trade-offs among several performance indexes. Compared with the benchmark controller design, the human-centered design is shown to largely improve the driving comfort.

"Event-Triggered Control for String-Stable Vehicle Platooning" by Dolk *et al*. develops an event-triggered control scheme and communication strategy to tackle the network-induced imperfections in the formation of vehicle platoons with small inter-vehicle distance. The goal is to reduce the utilization of communication resources while maintaining the desired closed-loop performance properties. The resulting L2 string-stable control strategy is experimentally validated by a platoon of several passenger vehicles. By limiting communication to only the important information, unnecessary transmissions can be avoided and, therefore, a string-stable platoon can be established over the wireless network.

"Object Matching for Inter-Vehicle Communication Systems—An IMM-Based Track Association Approach with Sequential Multiple Hypothesis Test" by Yiuan *et al*. provides an industrial point of view on the unique challenges posed by exploiting cooperative information for environment perception in autonomous driving. The authors describe a dedicated short-range communication (DSRC) system to provide a low-latency inter-vehicle wireless communication channel. The task is to build a record linkage between the onboard sensor data and the corresponding DSRC-transmitted remote vehicle information when both sets belong to a same object, for the purpose of enhancing host vehicle environment perceiving capability and reliability. The object match is solved as a statistically reliable track-to-track association problem. An interacting multiple model approach using the sequential multiple hypothesis test (IMM-SMHT) is introduced to provide a ubiquitous solution to handle different situations in complicated driving scenarios. Based on the prototype built, the authors designed meaningful use cases for creating functionality modules. The IMM-SMHT approach was tested in real traffic on United States roads and the paper shows promising object-matching performance of significant practical implications.

In "Autonomous Campus Mobility Services using Driverless Taxi", Kim *et al*. presents a driverless taxi for collaborative campus mobility services. A college campus has a unique mobility context in terms of layout, population, mobility demand, and pattern. This paper suggests a driverless taxi service to offer point-to-point shared mobility on a campus and demonstrates the feasibility of this service on a 4.5-km long campus road at Seoul National University. The service is currently in operation.

In "An Algorithm for Supervised Driving of Cooperative Semi-Autonomous Vehicles", Altché *et al*. propose a cooperative framework to safely coordinate semi-autonomous vehicles, removing the risk of collision or deadlocks while remaining compatible with human driving. More specifically, the authors present a supervised coordination scheme that overrides control inputs from human drivers when they would result in an unsafe or blocked situation. To avoid unnecessary intervention and remain compatible with human driving, overriding only occurs when collisions or deadlocks are imminent. In this case, safe overriding controls are chosen while ensuring they deviate minimally from those originally requested by the drivers. Simulation results based on a realistic physics simulator show that this approach is scalable to real-world scenarios and computations can be performed in real time on a standard computer for up to a dozen simultaneous vehicles.

"Pedestrian Movement Direction Recognition Using Convolutional Neural Networks" by Dominguez-Sanchez *et al.* presents a CNN-based technique of leveraging current pedestrian-detection techniques (HOG-linSVM) to generate a sum of subtracted frames by the flow estimation around the detected pedestrian. It is used as an input for the proposed modified versions of various CNN networks such as AlexNet, GoogleNet, and ResNet. Furthermore, for a neural network of achieving reliable performance, the authors have created a new dataset and analyzed the importance of training in a known dataset.

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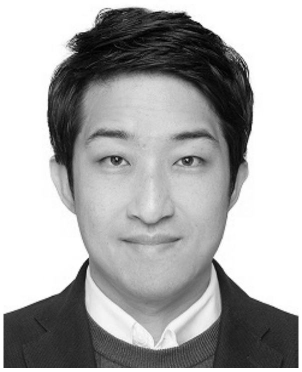

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