Received 18 May 2021; revised 19 July 2021; accepted 22 July 2021. Date of publication 26 July 2021; date of current version 9 August 2021.

Digital Object Identifier 10.1109/OJITS.2021.3099976

Opportunities and Challenges in Cooperative Road Vehicle Automation

STEVEN E. SHLADOVER (Member, IEEE)

California PATH Program, Institute of Transportation Studies, University of California at Berkeley, Berkeley, CA 94804, USA

CORRESPONDING AUTHOR: S. E. SHLADOVER (e-mail: sess@berkeley.edu)

This work was supported in part by the Berkeley Research Impact Initiative (BRII) sponsored by the UC Berkeley Library.

ABSTRACT This paper provides an introduction to the opportunities for improving the performance of road transportation automation systems by use of vehicle-vehicle and vehicle-infrastructure communication and cooperation. Four different types of cooperative driving automation are defined and examples of the functionality enabled by each are described. Although the benefits of cooperative automation are significant, there are also significant challenges to its widespread deployment, which are also described. The risks of over-reliance on communication for cooperative automation implementations are also discussed to provide a balanced view of appropriate levels of cooperation.

INDEX TERMS Automated driving, automated vehicles, cooperative automated driving, cooperative driving automation.

I. INTRODUCTION

PRIVATE companies in the automotive and information technology industries are investing heavily in the development of Automated Driving Systems (ADS), the systems that will be capable of performing the complete dynamic driving task (DDT) under certain conditions, defined by the system's operational design domain (ODD) [1]. This means that they will be able to replace human driver functions during portions of some trips and in some cases will be able to perform complete trips without human intervention. The future tense is used here because although these capabilities are under active development there are only a few very limited instances in which they have been introduced into public use to perform a real transportation function.

Almost all of these ADS have been designed to operate autonomously, based entirely on the information collected by their onboard sensors, and without the benefit of external information from, or active coordination with, other road users or the roadway infrastructure. Cooperative road vehicle automation, in contrast, takes advantage of these additional sources of information and coordination by means of wireless vehicle-vehicle (V2V), vehicle-infrastructure (V2I) or more general vehicle-to-anything (V2X) communications.

ADS developers have tended to avoid cooperative automation for several reasons:

- Reluctance to trust the accuracy of information received from unknown or unverified external sources;
- Concerns about the lack of incremental benefits to the first adopters of cooperative systems, who do not gain benefits until enough other entities are equipped;
- Skepticism about the willingness and ability of public authorities to install and maintain cooperative infrastructure-based devices;
- Concerns about the rate of growth in the market for other cooperative entities in the absence of government mandates or strong financial incentives;
- Uncertainties about the relative liability exposure of multiple entities when a crash occurs involving a vehicle using cooperative automation;
- Slow development of definitive standards to ensure interoperability of all cooperative entities;
- Political uncertainties about the availability of the wireless spectrum needed for V2X communications.

Despite these concerns, there are compelling reasons to pursue cooperative road vehicle automation based on the benefits that it can provide to individual users and to the performance of the transportation system as a whole. Although the roadway network is the dominant means for moving people and goods, especially in North America, it suffers from a lower level of cooperation than the other primary transportation modes (rail, air, marine). In each of those other modes, there is closer coordination of decision making

The review of this article was arranged by Associate Editor Jiaqi Ma.

and control between the infrastructure and the vehicles than there is in road transportation.

It has been easier to achieve cooperation between the vehicles and their supporting infrastructure in the other modes for several reasons:

- Their vehicles are predominantly operated commercially, rather than being operated by private individuals, with strong economic incentives to maximize efficiency and safety;
- They have much smaller numbers of vehicles, each of which is more expensive than a private automobile, so that the incremental cost for implementing cooperative features is a smaller fraction of the total cost of ownership;
- The industry culture is accustomed to strong federal government regulatory oversight, especially for safety in the commercial airline and maritime industries;
- The railroads have common ownership and decision making for infrastructure and vehicles.

That close coordination enables operation as a well-integrated system of systems, with attendant benefits in efficiency and safety that the road transportation network could emulate. These opportunities were recognized by the U.S. Federal Highway Administration in creating a research platform called CARMA (Connected Automated Research for Modeling and Analysis) to develop and explore the possibilities for cooperative automation [2].

The rest of this paper explores the opportunities and challenges associated with adding cooperative elements to road vehicle automation. It begins with an explanation of the different levels of automation and cooperation and the relevant terminology for describing those, and then explains the kinds of benefits that can be gained from each level of cooperation. Examples of safety and efficiency benefits from cooperative automation are discussed in more detail. Finally, cautionary examples about over-emphasis on cooperative automation functions are introduced in the context of cyber-security, cooperative perception and cloud-based distributed architectures for automation.

II. TERMINOLOGY FOR COOPERATIVE DRIVING AUTOMATION

SAE International has developed precise definitions to describe important aspects of cooperative automation, including both levels of automation and levels of cooperation. Precise terminology is important to ensure accurate technical communication and avoid misunderstandings, so the relevant terminology is introduced here.

The definitive terminology for road vehicle automation is in the SAE J3016 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, which was originally published in 2014 and received its third revision in April 2021 [1]. Since its terminology has been in widespread use already, only a few highlights are discussed here. The term "driving automation" is used to refer to all levels of driving automation, including the lower levels that require continuous supervision by a driver, which are classified as "driver support" systems. This distinguishes them from the "Automated Driving Systems (ADS)", which are capable of performing the complete "dynamic driving task (DDT)" under defined conditions, which are referred to as the "operational design domain (ODD)". The DDT refers to the operational and tactical driving tasks, while excluding the strategic tasks of driving such as trip planning and route selection.

In 2020, SAE published J3216 Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles [3] as a complement to J3016. It defines cooperative driving automation (CDA) as: "Automation that uses M2M [machine to machine] communication to enable cooperation among two or more entities with capable communications technology and is intended to facilitate the safer, more efficient movement of road users, including enhancing performance of the DDT for a vehicle with driving automation feature(s) engaged." It defines four classes of cooperation that are orthogonal to the six levels of automation that were defined in J3016. These four classes of cooperation provide a clear structure for discussing the different ways in which entities (vehicles, vulnerable road users, or local or centralized traffic control devices) can cooperate in the operation of driving automation systems. The letter designations for these classes of cooperation are intended to be combined with the numerical designations of the levels of automation to produce informative descriptors of specific systems (e.g., a Level 1A cooperative adaptive cruise control system or a Level 4C automated highway merging system). The classes of cooperation are defined as:

Status-Sharing Cooperation (Class A): Perception information about the traffic environment and information about the sending entity provided by the sending entity for potential utilization by receiving entities. ("Here I am, and here is what I see.")

Intent-Sharing Cooperation (Class B): Information about planned future actions of the sending entity provided by that entity for potential utilization by receiving entities. ("This is what I plan to do.")

Agreement-Seeking Cooperation (Class C): A sequence of collaborative messages among specific CDA devices intended to influence local planning of specific DDT-related actions. ("Let's do this together.")

Prescriptive Cooperation (Class D): The direction of specific action(s) to specific traffic participants for imminent performance of the DDT or performance of a particular task by a road operator (e.g., changing traffic signal phase), provided by a prescribing CDA device agent(s) and adhered to by a receiving CDA device agent(s). ("I will do as directed.").

The classes are defined based on the ways in which the recipients of the information are expected to respond to the information. Class A information is about the current situation (involving the status of the sender and situations that its sensors can perceive) so that the recipient has more complete knowledge on which to base its decisions, while Class B is about planned future actions, with an implicit request for the recipient to modify its behavior to accommodate those changes. Class C is an active negotiation, while Class D requires the recipient to take an involuntary action. These general definitions of classes were deliberately defined to apply equally to fixed infrastructure and mobile entities (vehicles or vulnerable road users), since each class could apply to V2V, V2P, V2I and I2V interactions. The examples that were provided in the SAE J3216 document were chosen to include each of these types of interactions, to assign them comparable importance.

III. CAPABILITIES ASSOCIATED WITH EACH CLASS OF COOPERATION

The four successive classes of cooperation represent increasing closeness of cooperation, with additional complexities associated with each increase. Each increase in cooperation opens new opportunities for enhancing the capabilities of the driving automation system.

A. STATUS-SHARING COOPERATION (CLASS A)

This is the most commonly described level of cooperation and the most straightforward. Each vehicle or vulnerable road user broadcasts information to describe its location, velocity vector, mass, dimensions and other important status (such as acceleration or braking commands) so that the others can use that to adjust their performance to smooth out traffic disturbances or avoid crashes. This level of cooperation is fundamental to cooperative collision avoidance [4] (based on use of the Basic Safety Message data) and cooperative adaptive cruise control (CACC) and platooning for enhanced vehicle-follower control [5]. Infrastructure-based traffic control devices broadcast their status such as traffic signal phase and time to next phase change (SPaT), speed advisories [6], [7] and alerts about potential hazards such as lane blockages or traffic jams ahead [8]. These are fundamental to intersection collision avoidance [9], [10] and eco-driving [11] applications. Future extensions could include sharing information that sensors (mounted on vehicles or roadside infrastructure) detect about the motions of unequipped vehicles or vulnerable road users, so that each road user can be made aware of hazards that are not within the field of regard of their own sensors but have been detected by other equipped entities.

This type of cooperation significantly enhances the information available to a driving automation system, so that it includes information that could not be obtained by any sensors mounted on the vehicle itself. Some of this information can only be known to the entities that transmit it (vehicle mass, acceleration or braking commands, traffic signal change countdowns) and represents information that would otherwise be unknowable to the driving automation system. Other information could be considered enhancements to the field of regard of the subject vehicle's sensors by providing information about other entities that are beyond the range of the sensors or are occluded by obstructions such as buildings on corners in urban areas or by road geometry (horizontal or vertical curves).

B. INTENT-SHARING COOPERATION (CLASS B)

This class of cooperation extends beyond Class A by including information about planned future actions. This could be an intended speed change or lane change or turning maneuver by a vehicle, an intended street crossing by a vulnerable road user, or a future traffic signal phase change by a traffic signal controller.

This type of information improves the ability of a driving automation system to predict the actions of other traffic participants so that it can plan a smoother, safer and more energy efficient trajectory. The kinds of information included here would not normally be detectable by any onboard sensor systems (although if human drivers used their directional signals more consistently the turning and lane changing maneuvers could indeed be predicted somewhat more reliably).

C. AGREEMENT-SEEKING COOPERATION (CLASS C)

This class of cooperation adds a further layer of complexity by engaging in a sequence of message exchanges to negotiate cooperative maneuvers. This can be particularly beneficial for merging and lane changing maneuvers [12], for which one party may need to yield to another to avoid a conflict, and for traversing uncontrolled intersections or intersections with four-way stop signs, where the right of way can be confirmed. These message exchanges can reduce the frequency and severity of right of way conflicts, with potentially significant benefits in safety and traffic flow smoothness, which can in turn reduce traffic congestion at bottlenecks and reduce energy consumption and emissions by smoothing traffic flow dynamics.

D. PRESCRIPTIVE COOPERATION (CLASS D)

This class of cooperation differs from the other classes because it is asymmetrical, in that one of entities has authority to demand specific responses from another. This could be a traffic signal controller commanding a stop by vehicles approaching a red signal or a regulatory speed limit sign commanding compliance with the speed limit. Law enforcement and emergency vehicles can demand priority or pre-emption from traffic signal controllers, and in the future they could potentially command other ADS-driven vehicles to yield to their demands for right of way. Fleet managers could also issue a variety of commands to the vehicles that are operated under their supervision.

In the longer term, prescriptive cooperation could enable a variety of more sophisticated emergency response strategies associated with traffic incidents or natural disasters, all the way up to mass evacuation scenarios.

Some of the potential future uses of prescriptive cooperation are likely to require careful consideration of political, legal and ethical issues to identify the boundaries between the decision authorities of the different entities. How much authority should a driving automation system or the human driver supervising its operation have to ignore a prescriptive message that commands a specific vehicle speed or maneuver if other information available to the vehicle's ADS weighs in favor of different behavior? What would be the division of responsibility for a crash that occurred when conflicting commands were being generated by different entities?

IV. OPPORTUNITIES TO ENHANCE SAFETY

The case for potentially mandating the inclusion of V2X communications in all new light-duty vehicles was justified based on a modest subset of the potential traffic safety benefits [13]. The general types of safety benefits associated with adding cooperative capabilities to automated driving are discussed here, building on the original focus on providing collision warnings to human drivers. Since the literature on this topic is extensive there is no attempt to provide a comprehensive literature review.

The concept of using V2V communications of detailed information about the vehicle location and velocity vector to facilitate collision warning and avoidance was initially promoted by General Motors (GM) in the early 2000s as a lower-cost alternative to equipping vehicles with extensive sensor suites to detect collision hazards. GM worked with PATH to prototype the concept using the test vehicles that were originally developed for the National Automated Highway Systems Consortium, and the initial test results [4] were sufficiently encouraging that GM developed subsequent prototype vehicles and convinced the other major automotive OEMs and NHTSA to join with them under the Crash Avoidance Metrics Partnership (CAMP) on a national program for cooperative collision warning (CCW). The CCW efforts provided the technical foundations for the development of the primary V2V standards in IEEE and SAE. Although these standards were initially developed for purposes of providing collision warnings to human drivers, it quickly became evident that the same cooperative data could just as well be extended to use for cooperative automation of driving at virtually no additional cost. Because the V2V communication standards were designed to be flexible, it was easy to apply to them to infrastructure to vehicle (I2V) cooperation as well.

The primary messages defined for CCW applications are the Basic Safety Message (BSM) to be sent by each vehicle and the Signal Phase and Timing (SPaT) and local intersection map [14] messages to be sent by the signal controller at each signalized intersection. These messages are fundamental to cooperative driving automation systems as well, since the same kind of information is needed for these applications.

The basic information provided through the exchange of messages designed for CCW enables a variety of cooperative driving automation applications that can enhance traffic safety. These applications include:

- Cooperative intersection collision avoidance – advance information about the movements of other vehicles or about traffic signal status that is used to command deceleration or stopping maneuvers by an ADS to avoid intersection crashes [9], [10];

- Vulnerable road user collision avoidance – information exchanges with pedestrians and cyclists that alert driving automation systems about their trajectories, and especially sudden changes in motion, that can be used to command evasive driving maneuvers by an ADS;

- Use of local weather information to advise an ADS about nearby or imminent adverse weather conditions that exceed the limits of its ODD so that the ADS can change its route to avoid the weather, reduce its speed if that will enable it to continue on its original route, or seek a safe location to park while waiting for the weather to improve;

- Use of V2V information to enable an ADS to negotiate maneuver priority with other vehicles' ADS for lane changing, merging and traversing uncontrolled intersections or intersections with 4-way stop signs;

- Use of I2V and V2V messaging to facilitate emergency vehicle priority relative to other vehicles driven by ADS (instructing the ADS how to safely yield to the emergency vehicle) and to advise ADS how to safely maneuver through work zones and incident locations;

- Use of V2V and I2V messaging to alert ADS driving on high-speed highways about the presence of stopped traffic at the end of congestion queues, so that they can decelerate before the stopped vehicles are detected by their forward ranging sensors;

- Use of I2V messaging to alert ADS about variable speed limit changes based on dynamic traffic or weather conditions.

V. OPPORTUNITIES TO IMPROVE TRAFFIC FLOW

The "other" important category of benefit associated with cooperative automation is the potential improvement in traffic flow, which can be measured in terms of increased bottleneck capacity, reduced travel time or delay, reduced energy consumption and emissions (of GHG and criteria pollutants) or enhanced smoothness and comfort of travel. The cooperative driving automation applications that improve traffic flow largely rely on the same V2V and I2V messages as the safety applications discussed in the previous sections, but these applications can gain further benefits from additional messages that are designed to stabilize vehicle following dynamics and reduce energy consumption and pollutant emissions.

Traffic flow improvements (increased stability, increased bottleneck capacity, reduced travel delays, reduced energy consumption and criteria pollutant emissions) associated with adding cooperative elements to driving automation include:

- V2I provision of traffic management guidance to ADS for speed harmonization based on variable speed advisories (VSA) or mandatory variable speed limits (VSL) designed to smooth traffic flow reduce the disturbances to traffic flow at bottlenecks [6], [7];

- V2I provision of traffic signal phase and timing information to approaching ADS enabling them to adjust their speed profiles based on advance knowledge of impending signal phase changes so that they can reduce the frequency of stops and the amount of excess energy use and emissions associated with acceleration and deceleration maneuvers [11];
- V2I provision of real-time traffic conditions throughout the network to ADS, enabling the ADS to adjust routing to minimize delays, congestion, energy use and emissions;
- V2I exchange of information at freeway onramps to provide for coordinated merging of entering vehicles into the mainline traffic stream, enabling cooperative ADS to adjust their speed profiles to reduce merging conflicts and their associated impacts on traffic flow, energy use and emissions [12];
- V2V exchange of information to facilitate merging and lane changing coordination among cooperative ADS vehicles at any location, including those that are not equipped with V2I capabilities [12];
- V2V exchange of information to support cooperative adaptive cruise control and platooning of vehicles, which enable closer and more stable ADS vehicle-following control, leading to higher flow capacity, reduced congestion, and savings in energy consumption and emissions [15], [16].

VI. CHALLENGES FOR COOPERATIVE AUTOMATION

The potential benefits from cooperative automation do not come entirely “for free”, but rather they have associated risks and costs. These can be classified into several groups of challenges.

- Dependence on uncertain and inhomogeneous deployment of needed cooperative devices on other vehicles, roadway infrastructure and vulnerable road users;
- Cyber-security threats associated with receiving data from external entities via wireless links and potentially performing some safety-critical and time-critical dynamic driving functions away from the vehicle;
- Challenges in establishing realistically scaled field operational tests to verify the real-world benefits and costs associated with cooperative automation (based on costs for deploying the number of vehicle and infrastructure devices that will be needed);
- Wireless data transfer costs and security vulnerabilities associated with some of the more ambitious cooperative concepts of sharing raw sensor data and distributing computational functions to edge and cloud-based computers.

A. DEPLOYMENT UNCERTAINTIES

The performance advantages of cooperative automation systems are based on the network effects of the interactions among vehicles, other road users, and roadside infrastructure devices. This means that no individual decision maker at an ADS development company, a vehicle fleet operator, a transportation infrastructure owner-operator or a private vehicle purchaser is able to predict or control the benefits that they will gain from their decision to develop, acquire or operate a cooperative automation vehicle or system. Those benefits will depend on the parallel decisions of their peers and the rest of the relevant stakeholders about selecting their own cooperative automation systems. The earliest adopters do not gain significant benefits at first, but they have to wait for enough other decision makers to apply the cooperative system in order to gain their benefits.

For vehicle-vehicle cooperative automation systems, the dependence on market penetration is quadratic because achieving the benefit depends on the product of the probabilities of the deployment decisions by owners of both interacting vehicles [17]. At 50% market penetration, only about 25% of the incremental benefits from cooperation are achievable, and it takes about 70% market penetration to gain half of the benefits of complete market penetration. For vehicle-infrastructure cooperative systems, the benefits to the vehicle users scale linearly with the fraction of the infrastructure that is equipped within the intended ODD for the system, which depends on the independent decisions of the infrastructure owner-operators in all the locations where the vehicle user travels.

This is a real impediment to deployment in the absence of coordinated government action. Financial incentives or regulatory pushes are likely to be needed to “prime the pump” for widespread deployment, based on anticipated societal benefits that exceed the benefits to the individual deployment decision makers, particularly the early deployers. Strong cases can be made for traffic safety and congestion benefits, including benefits that accrue to the general traveling public. That was behind the original U.S. DOT proposal in 2017 to create FMVSS 150 to mandate installation of DSRC radios to broadcast basic safety messages on all new vehicles after a certain date [13], so that the population of equipped vehicles would grow rapidly and the large production volume of devices to meet that mandate would keep the cost per device relatively low. Unfortunately that rule was not promulgated so a major opportunity was lost. The U.S. DOT could provide funding directly to state and local agencies to support the installation and operation of the cooperative infrastructure devices, but this would be competing with other transportation funding priorities so it will again be necessary to provide authoritative information about the expected benefits in order to support prioritization of this investment.

B. CYBERSECURITY THREATS

Each device that communicates data can be vulnerable to cyberattacks, so a high priority needs to be placed on securing all of the communication links used for cooperative automation. This is well recognized in the industry and substantial attention has already been devoted to it. The threat has been exaggerated at times by observers who fail to recognize that all of the sensor systems that are used for environment perception by driving automation systems are also vulnerable to cyberattacks, so the threat is not peculiar to the cooperative systems. Indeed, as explained in [18] the additional information that can be provided via V2V and V2I communications can be used to help identify potential attacks on the perception sensors by serving as independent data sources. A wider range of independent information sources can make the system more robust against cyberattacks when those sources are well secured and are used in a carefully designed data fusion framework to produce best estimates of the real situation confronting the driving automation system.

A well-designed driving automation system will retain as much as possible of the safety-critical and time-critical information collection and decision making local to the vehicle to minimize the opportunities for external interference. The safety-critical software kernel needs to be kept as small and simple as possible and contained as tightly as possible within the high-bandwidth local control loop on the host vehicle. The V2X information should be used to augment the primary information obtained from the host vehicle's own sensors to minimize the potential impacts on performance and safety of delays or corruption of this information. It can also be used for corroboration of primary sensor information, serving as another input to the data fusion process that can be used to help identify discrepancies that could signal a fault or a cyberattack on any of the data sources. This reduces the vulnerability of the system to cyberattacks and to communication and computational latencies.

C. SCALING FIELD OPERATIONAL TESTS

Designing a realistic field operational test for cooperative automation systems is challenging because of the strong scale effects. As already noted, the benefits of cooperative automation scale strongly with the density of cooperative devices among all interacting entities (vehicles, other road users and roadside infrastructure). These entities need to interact with each other naturalistically, reflecting normal patterns of travel, yet under normal conditions the road users would normally travel over a wide range of locations in the course of a day, and would only occasionally be in close proximity to each other and to specific roadside devices. These factors point toward the need for very large field operational tests, involving large numbers of vehicles and devices. The costs and logistical and institutional challenges of organizing such large tests are daunting.

The practical challenges of staging large naturalistic field operational tests mean that it will probably be necessary to compromise on the realism of the tests in various ways. Several approaches are possible, leading to differing compromises on realism:

- Sacrifice the naturalistic aspect of traveler behavior and stage the movements of vehicles and other road users deliberately, with paid or volunteer test subjects driving the vehicles and walking and cycling through the test area to create interactions that can be recorded and analyzed. This is still likely to be expensive because of the labor and equipment costs, but it should produce data about the performance of the wireless technology, the vehicle systems and the traffic congestion impacts. However, it will not produce measurements of safety impacts or of effects on traveler decisions.

- Confine the testing to commercial and public service fleet vehicles equipped for cooperative automation that regularly travel within a limited geographical area and collect data on their naturalistic interactions with each other and other traffic. This narrows the driver population to professional drivers at work and makes it hard to collect data on interactions with vulnerable road users. A large number of vehicles and long duration of testing will be needed to collect statistically valid safety data because of the rarity of crashes and near-crash events. Because of vehicle density considerations, it would also have to be confined to dense urban areas and is not likely to be applicable to highway driving.

- Concentrate on traffic simulations rather than physical testing, and use limited physical testing to define and calibrate models of system performance and driver behavior. Computer simulations can be designed to represent large numbers of vehicles and vulnerable road users and their interactions and to create a large number of encounters for analysis. The great challenge with this approach involves how to create a sufficiently realistic simulation to generate valid results. Existing simulations are approaching the level of being able to represent traffic congestion effects and their related energy and emissions impacts, but are not close to being able to represent the safety impacts or the driver behavioral responses. It is questionable whether simulations of cooperative automation systems could be validated to a sufficient level that their results could be used to justify major policy changes or investments of resources on cooperative automation systems at a local, state or national level.

Additional research is worth pursuing to determine the practicality of combining these compromised approaches in ways that enable the strengths of one approach to compensate for the weaknesses of the others so that the combination could produce sufficiently credible results.

D. COOPERATIVE SYSTEMS BASED ON UNCONSTRAINED DATA EXCHANGES

The recent excitement about 5G cellular wireless communication has produced some conceptual notions of cooperative automation based on wireless exchanges of massive amounts of data. The cellular network operators and equipment suppliers established the Next-Generation Mobile Networks Alliance (https://www.ngmn.org/) to seek opportunities to expand the applications of cellular data transfer to generate the revenue streams needed to support their investments in expanding their networks. Their concepts need to be assessed based on the value they could provide to the transportation system operators and users rather than to the suppliers of the technology.

The computational resources that support automated driving functions can be distributed in different ways for different

ADS system designs. Based on general considerations of hierarchical system architectures [19], [20] the functions that have the widest geographical scope and slowest dynamics are best located centrally, while at the opposite end of the spectrum those with the fastest dynamics and narrowest geographical scope (which also tend to be the most safety critical) should be distributed most widely, to the precise locations (entities) where they are needed. The traffic management and route guidance functions would thereby be centralized while the environment perception and vehicle motion control functions would be executed locally in each vehicle.

There have been recent suggestions [21], [22] that the computationally intensive driving environment perception, data fusion and path planning functions should be performed by combinations of centralized cloud and infrastructure-based distributed edge computing systems, networked with each other and connected with the vehicles by high-bandwidth and low-latency wireless links. This would reduce the computation burdens on the vehicles, in the interest of reducing their computational equipment costs and computational energy consumption, while increasing wireless communication equipment and data communication service costs, with uncertain net cost implications. Regardless of whether the net cost is increased or decreased, such an allocation of time-critical and safety critical computations from on-board to off-board locations raises multiple concerns.

- Opening new attack surfaces for hackers – the data uplinks and downlinks and the off-board computational facilities. These would become particularly attractive attack surfaces because of the opportunity to disrupt the operations of many vehicles with a single attack.
- Opening single-point failure vulnerabilities unless all of the communication and off-board computational facilities are designed with heavy redundancy and fault tolerance.
- Making basic vehicle safety functions vulnerable to disruption from communication interference caused by man-made or natural sources (electrical storms, earthquakes, terrorist attacks, ...).
- Reducing transportation system resilience to disruptions from large-scale disasters that cripple the centralized resources (regional power failures, hurricanes, earthquakes, insurrections, terrorist attacks ...). If the ADS were able to continue operating without centralized resources in such situations they would be much better able to support the public in coping with other consequences of these disasters, for example in large-scale evacuations from impacted regions.
- Even if the centralized resources were not crippled by a large-scale disaster, they would be placed under extreme operational stress because large numbers of ADS would be required to operate under the most complicated and demanding conditions simultaneously. This means that the central computational and communication resources would have to be designed and built to handle such a severe peak situation even if it was expected to be very rare, which points toward an extremely costly endeavor.

Cooperative perception of the driving environment is a promising option for improving the ability of ADS to detect, recognize and track the motions of any objects that could represent hazards. Regardless of the completeness of the sensor suite installed on an ADS-equipped vehicle, those sensors will not be able to see all of the potential hazards. Some hazards will be beyond the maximum range of the sensors (e.g., stopped traffic at the end of a congestion queue on a high-speed motorway), while others will be occluded from view by high-profile vehicles in the vicinity of the subject vehicle or by the physical infrastructure (buildings close to the corners in urban settings, horizontal or vertical curvatures on roads in hilly areas). Even if these hazards are not visible to the subject vehicle, they could be readily visible to sensors on other nearby vehicles or to roadside sensors mounted at key locations where occlusions are most prevalent (complicated urban intersections, highway interchanges, blind rural intersections, mountain curves). If the roadside sensors and equipped vehicles broadcast the hazard information that they have detected, this can provide important inputs to the sensor data fusion and hazard detection systems on the vehicles whose views of these hazards are currently occluded. This is one of the most promising opportunities for Class A status-sharing cooperation, enabling performance that is not possible without cooperation.

Cooperative perception can be achieved by sharing different levels of information about the detected objects. At the simplest level, each vehicle [23], [24] and roadside sensor installation [25] does its own sensor data processing and fusion to produce its best estimate of the location, velocity vector, size and classification of the target object (vehicle, pedestrian, cyclist, animal, or general inanimate object). A compact description of those attributes, representing the target tracking information for each object, is broadcast periodically, with time stamps to aid synchronization, so that each receiving vehicle can incorporate that information efficiently into its perception system's threat assessments. This can be accomplished with a modest level of wireless data traffic. SAE in the U.S. and ETSI in Europe have initiated efforts to define the standards for generating efficient and compact messages to use to share this information.

In contrast to the simple cooperative perception approach described above, there have been proposals for more elaborate cooperative perception approaches that would share raw sensor data rather than the synthesized target tracks, based on wireless industry commercial initiatives but not documented in the technical literature, except for some limited estimates of their communication needs [26]. Under this concept, each vehicle or roadside sensor station would broadcast the raw data from its sensors (lidar point clouds, video images, radar returns) so that each receiving vehicle could fuse that raw data with the raw data from its own onboard sensors to produce refined estimates of the target location, velocity vector, size and classification. This approach would pose several serious practical challenges.

- The volume of data that would have to be broadcast over the wireless channels would be extremely large. For each video camera, the raw data rate would be on the order of 100 to 1000 Mb/s (depending on resolution chosen), while each radar and each lidar would generate hundreds of Mb/s of raw data. When considering that a Level 4 ADS would have to be equipped with multiple sensors of each of these types, the combined raw data rate per vehicle could be in the range of 1 to 2 GB/s. With dozens to hundreds of vehicles sharing this type of data within safety-critical proximity of each other in a congested urban area, the additional one or two orders of magnitude of data traffic makes this an even more daunting burden on the wireless communication system.
- Although the wireless channels will be crowded with sensor data from many different vehicles and roadside devices, only a small fraction of that information will be relevant to any individual vehicle monitoring those channels. It will be a complicated task for the computer on each vehicle to sort through the massive amount of incoming data to find the relevant fraction.
- The sensors on the different vehicles and infrastructure locations will be perceiving the target objects from different angles and distances. It will be necessary to know the sensor locations and orientations with very high accuracy in order to fuse these separate measurements into an accurate representation of the target object, and that fusion process will be exceedingly complicated and computationally intensive.
- The raw sensor data need to be processed using proprietary software from the specific device vendor to convert it into useful information about the target objects. Each vehicle would need to run that proprietary software from the vendors of the sensors on all of the other vehicles in order to decipher their raw data. Even in a mature, consolidated market for sensors there would probably be at least three or four vendors of each primary type of sensor (radar, lidar, video), which indicates that each vehicle would need to run the sensor decoding software from ten or so vendors of sensors that are not even installed on its vehicle. This adds another layer of cost and complexity.

Considering all of these complications, the notion of cooperative perception using raw sensor data would only appear to be appealing to suppliers of high-capacity computers and wireless devices and operators of the wireless networks that would generate revenue from the associated data traffic.

VII. CONCLUDING REMARKS

Use of wireless communication of data among vehicles and between vehicles and the roadway infrastructure and traffic management systems can enable road transportation to function as a properly integrated transportation system, analogous to the rail and air transportation systems. When combined with driving automation technology, this offers the potential for significant improvements in safety, efficiency and environmental impacts compared to autonomous automation of vehicles. However, successful deployment of cooperative driving automation systems is not assured because of several practical challenges to deployment that need to be overcome. The organizations that work on designing and developing the cooperative driving automation systems also need to give careful consideration to the information architecture of the system to make sure that it makes efficient use of communication and computational resources and is properly protected from risks of single-point failures and cyberattacks.

REFERENCES

[1] *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, SAE International Standard J3016, 2021.
[2] *CARMA Program Overview*. Accessed: May 8, 2021. [Online]. Available: https://highways.dot.gov/research/operations/CARMA
[3] *Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles*, SAE International Standard J3216, 2020.
[4] R. Sengupta, S. Rezaei, S. E. Shladover, D. Cody, S. Dickey, and H. Krishnan, "Cooperative collision warning systems: Concept definition and experimental implementation," *J. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 143–155, 2007.
[5] S. E. Shladover, C. Nowakowski, X.-Y. Lu, and R. Ferlis, "Cooperative adaptive cruise control: Definitions and operating concepts," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2489, pp. 145–152, 2015.
[6] J. Ma *et al.*, "Freeway speed harmonization," *IEEE Trans. Intell. Veh.*, vol. 1, no. 1, pp. 78–89, Mar. 2016.
[7] X.-Y. Lu and S. E. Shladover, "Review of variable speed limits and advisories: Theory, algorithms and practice," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2423, pp. 15–23, 2014.
[8] C. Nowakowski, D. Vizzini, S. Datta Gupta, and R. Sengupta, "Evaluation of a real-time, freeway end-of-queue alerting system to promote driver situational awareness," in *Proc. 91st Annu. TRB Meeting*, Washington, DC, USA, 2012, pp. 37–43.
[9] M. Maile and L. Delgrossi, "Cooperative intersection collision avoidance system for violations (CICAS-V) for prevention of violation-based intersection crashes," in *Proc. 21st (ESV) Int. Tech. Conf. Enhanced Safety Veh.*, Jun. 2009, Art. no. 09-0118.
[10] G. McHale and V. McClean, "Gap assistance projects within the CICAS program," *Proc. 14th World Congr. Intell. Transp. Syst. (ITS)*, Oct. 2007.
[11] H. Xia *et al.*, "Field operational testing of eco-approach technology at a fixed-time signalized intersection," in *Proc. 15th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Sep. 2012, pp. 188–193.
[12] F.-C. Chou, S. E. Shladover, and G. Bansal, "Coordinated merge control based on V2V communication," in *Proc. IEEE Veh. Netw. Conf.*, Dec. 2016, pp. 1–8.
[13] (Sep. 2015). *NHTSA Office of Regulatory Analysis and Evaluation, Preliminary Regulatory Impact Analysis of FMVSS 150: Vehicle-To-Vehicle Communication Technology for Light Vehicles*. [Online]. Available: https://www.federalregister.gov/documents/2017/01/12/2016-31059/federal-motor-vehicle-safety-standards-v2v-communications
[14] *V2X Communications Message Set Dictionary*, SAE International Standard J2735, 2020.
[15] H. Liu, X. Kan, S. E. Shladover, X. Lu, and R. E. Ferlis, "Modeling the effectiveness of cooperative adaptive cruise control for multi-lane freeway with mixed traffic flow," *Transp. Res. C, Emerg. Technol.*, vol. 95, pp. 261–279, Oct. 2018.
[16] H. Liu, S. E. Shladover, X.-Y. Lu, and X. Kan, "Freeway vehicle fuel efficiency improvement via cooperative adaptive cruise control," *J. Intell. Transp. Syst.*, to be published. [Online]. Available: https://doi.org/10.1080/15472450.2020.1720673
[17] S. E. Shladover, G. Polatkan, R. Sengupta, J. VanderWerf, M. Ergen, and B. Bougler, "Dependence of cooperative vehicle system (CVS) Performance on market penetration," *Transp. Res. Rec. Transp. Res. Board*, vol. 2000, pp. 121–127, 2007.
[18] J. Petit and S. E. Shladover, "Potential cyberattacks on automated vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 546–556, Apr. 2015.

[19] P. Varaiya, “Smart cars on smart roads: Problems of control,” *IEEE Trans. Autom. Control*, vol. 38, no. 2, pp. 195–207, Feb. 1993.

[20] J. S. Albus and A. M. Meystel, “A reference model architecture for design and implementation of intelligent control in large and complex systems,” *Int. J. Intell. Control Syst.*, vol. 1, no. 1, pp. 15–30, 1996.

[21] J. Sharma, “The evolving role of wireless technology to support highly automated driving,” in *Proc. ITU-UNECE Future Netw. Car Symp.*, Mar. 2021. [Online]. Available: https://www.youtube.com/watch?v=uL2dRHuX2Cc

[22] N. Duggal, “Communication for highly automated driving,” presented at ITU-UNECE Future Netw. Car Symp., Mar. 2021. [Online]. Available: https://www.youtube.com/watch?v=IFQcL6yfBso

[23] H.-J. Günther, B. Mennenga, O. Trauer, R. Riebl, and L. Wolf, “Realizing collective perception in a vehicle,” in *Proc. IEEE Veh. Netw. Conf.*, 2016, pp. 1–8.

[24] M. Tsukada, T. Oi, M. Kitazawa, and H. Esaki, “Networked roadside perception units for autonomous driving,” *Sensors*, vol. 20, no. 18, pp. 5320–5340, 2020.

[25] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, “Generation of cooperative perception messages for connected and automated vehicles,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 16336–16341, Dec. 2020.

[26] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, Jr., “Combining millimeter-wave radar and communication paradigms for automotive applications: A signal processing approach,” Dept. Transp., Univ. Texas, Austin, TX, USA, Rep. D-STOP/2016/106, 2016.

STEVEN E. SHLADOVER (Member, IEEE) received the B.S., M.S., and Sc.D. degrees in mechanical engineering with a specialization in dynamic systems and control from the Massachusetts Institute of Technology, Cambridge, USA.

He began conducting research on vehicle automation with the Massachusetts Institute of Technology in 1973. He was with Systems Control, Inc., and Systems Control Technology, Inc., for 11 years, where he led the company’s efforts in transportation systems engineering and computer-aided control engineering software products. He leads the U.S. delegation to ISO/TC204/WG14, which is developing international standards for vehicle-roadway warning and control systems. 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. He 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, and the Transportation Research Board. He was the Chairman of the Committee on Intelligent Transportation Systems from 2004 to 2010, Vehicle-Highway Automation from 2013 to 2019, and the Advanced Vehicle Control and Safety Systems Committee of the Intelligent Transportation Society of America from its founding from 1991 to 1997.