This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

A Survey on Cooperative Architectures and Maneuvers for Connected and Automated Vehicles

Bernhard Häfner, Vaibhav Bajpai, Jörg Ott, and Georg A. Schmitt

***Abstract*—With increasing connectivity, more and more advanced forms of cooperation among vehicles have become possible. Research has shown that vehicle-to-vehicle communication can improve road safety. However, more recent research advances regarding complex interactions such as cooperative maneuver negotiation have not yet gained much attention. Thus, in this survey, we analyze proposals for maneuver coordination protocols among automated vehicles. We include the communication, computation, and decision-making architectures commonly employed and a categorization scheme for different application-layer protocols enabling cooperative maneuvers. Next, we summarize related standardization, industry alliances, and research projects. As this field of research is still emerging, we also identify the diverse challenges that lie ahead before cooperative maneuver negotiations among automated vehicles can become a reality.**

***Index Terms*—Automated driving, automated vehicles, cooperation, cooperative maneuvers, joint maneuvers, maneuver negotiation, Vehicle-to-Everything (V2X), Vehicle-to-Vehicle (V2V), vehicular communication, vehicular networks.**

I. INTRODUCTION

FUTURE MOBILITY will not be comparable to a ride with today's vehicles. During the present decade (2020-2029), driving automation is expected to make further progress and potentially allow drivers to perform other tasks while commuting [1]. Around the globe, car manufacturers are moving away from the vision of building automated and autonomous vehicles that are completely autarkic from their surroundings and towards including connectivity and communication into their cars. Recent surveys cover the benefits of such communication for automated and autonomous driving [2], [3]. In a connected future of mobility, all vehicles will be connected to the Internet (V2N), as well as directly communicating to other vehicles via vehicle-to-vehicle (V2V) communication, to the roadside infrastructure (V2I), and even to others such as pedestrians (V2P). This connected ecosystem of vehicle-to-everything (V2X), also called the Internet of vehicles (IoV) [4]–[6], will enable higher safety, higher traffic efficiency, and more driving comfort [7].

Recent studies indicate that connectivity and digital services have become increasingly important criteria for car purchase decisions, especially for young customers. According to McKinsey, 58% of car buyers in China, 41% of those in the US, and also 24% of those in Germany would switch brands for a better connectivity offer, meaning remote access to and Internet connectivity of the car [8]. This exerts pressure on car manufacturers with traditionally long development cycles to converge more towards the development speed of the smartphone industry, where frequent updates and hardware purchases are prevalent. In contrast, the average age of light vehicles on US roads, for example, is 11.6 years [9].

Connected services have improved over the last years. Going beyond entertainment, sharing information with traffic management systems can be beneficial for the environment. By that, connected vehicles can positively affect fuel consumption, gasoline emissions, and traffic congestion [10]–[13]. Besides, even basic V2V communication has shown to improve safety for automated driving (AD) applications like platooning [14], [15].

Regarding the latter, research is ongoing regarding open challenges of basic safety services (e.g., the most suitable communication technology [22]–[27], coexistence between several technologies [28], or test methods [29]). At the same time, governments and industries are evaluating how to start deployments of V2X.

It is only recently that researchers have begun investigating how to enable interactively enabling cooperative maneuvers among automated vehicles, which is the main focus of this paper. As described in detail in Section II-B, we understand cooperative maneuvers in the sense of cooperatively negotiating and executing driving actions towards a common goal. Those cooperative maneuvers are based on different architectures regarding communication schemes, computational load, and decision-making. This is what we comprise under the term *cooperation architectures*, reviewed in detail in Section III. Most approaches for cooperative driving mainly involve automated vehicles, thus exceeding the research solely involving warnings or information displayed to human drivers.

A. *Related Surveys*

Many studies, standards, and other documents have been published on vehicular communication or AD, respectively. Surveys about V2X cover, e.g., physical and medium access control (MAC) layer of access technologies [30]–[32], message routing [33], [34], or security and privacy [35]–[39]. Those about AD cover, e.g., control [40], motion planning [41]–[44], or sensing and mapping [45]. General surveys on V2X [46] and AD [47], [48] also exist.

Regarding the intersection of the two, *cooperative maneuvers*, only fewer surveys exist. As outlined in more detail in Section II-B, this new field uses V2X communication to enable

B. Häfner and G. A. Schmitt are with BMW Group Development, 80788 Munich, Germany (e-mail: bernhard.haefner@bmw.de; georg.schmitt@bmw.de).

V. Bajpai and J. Ott are with the Department of Informatics, Technische Universität München, 85748 Garching near Munich, Germany (e-mail: bajpaiv@in.tum.de; ott@in.tum.de).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

TABLE I
RELATED SURVEYS FROM THE FIELD OF COOPERATIVE MANEUVERS

Survey	Scope	Contribution	Relevance to Cooperative Maneuvers
[16]	General (macro-scale)	Categorize coordination problems for CAVs, e.g., ride sharing	Taking a high-elevation viewpoint on cooperative maneuvers, mostly as ressource allocation problems.
Our work	General (micro-scale)	Categorize cooperative maneuver protocols on single maneuver level, e.g., lane chage	First research review on the topic of cooperative maneuver protocols and architectures.
[17]	Platooning	Give overview on overall platooning, e.g., control, communication, simulation	Platooning as special case of cooperative maneuvers (excluded in our survey).
[18]	Platoon safety	Give overview on safety approaches for platoons	Point out that common safety standards like ISO26262 [19] are insufficient for cooperative systems.
[7]	Traffic flow	Categorize methods to coordinate traffic	Cooperative maneuvers can help increase traffic flow.
[20]	Intersection management	Categorize approaches on cooperative intersection management	Some approaches, e.g., tile reservation, could be applied for general cooperative maneuvers.
[21]	Intersection management	Give overview on centralized and decentralized intersection management approaches	Some approaches could be applied for general cooperative maneuvers.

joint driving maneuvers among automated vehicles. Some papers [17], [18] review studies on the special case of platooning, meaning several vehicles driving in unison in close distance to each other. Another special case is intersection coordination, which several reviews [7], [20], [21] have surveyed. Mariani *et al.* [16] survey the coordination of autonomous vehicles and categorize the implementations of scenarios like ride hailing, parking spot allocation, and traffic flow optimization according to the degree of autonomy given to individual vehicles.

Further context and existing surveys are given in Section II-A.

B. Objective and Contributions

The objective of this paper is to provide an in-depth understanding of cooperative maneuvers in general, especially application-layer protocols and enabling architectures. Different to Mariani *et al.* we do not look at (large-scale) resource optimization or distribution problems, but focus on proposals for small-scale, local cooperation. Table I gives an overview on the related surveys on cooperative maneuvers and how our paper's focus differs from them.

The main contributions of our survey are

- Outlining the history of V2X communication and the inter-dependencies of related research fields in Section II.
- Categorizing architectures used for enabling cooperative maneuvers in Section III.
- Comparing application-layer protocols for cooperative maneuvers along several characteristics in Section IV.
- Giving an overview on global standardization activities and research projects related to advanced V2X services including cooperative maneuvers in Section V.

C. Organization

The remainder of this paper is structured as follows: In Section II-A, we outline the history of vehicular communication and define the scope of this survey, including key definitions. In In Section III, cooperation architectures for cooperative use cases are presented. In Section IV, we review current research on cooperative maneuvers. In Section V, we summarize current standardization efforts, industry activities, and funded projects related to V2X and advanced vehicular cooperation. We then outline directions and challenges for future research in Section VI, before concluding the paper in Section VII. In the appendix, we provide a list of used acronyms.

II. CONTEXT, SCOPE, AND TERMINOLOGY

In this section, we give the reader an overview on the historical development of V2X that lead to the research on cooperative maneuvers (Section II-A) which are the focus of this survey. Section II-B then delineates the scope of this paper and gives key definitions.

A. Historical Perspective

Starting in the late 1990s, studies have investigated what benefits communication could have for vehicles [57], [58] and subsequently, vehicular ad-hoc network (VANET) research emerged [59]. In the following, we describe the most popular research fields related to vehicular networks, following Fig. 1.

The first application was broadcasting beacons to discover neighboring vehicles. This was standardized in 2006 by the SAE International (SAE) [49], and in 2010 by the European Telecommunications Standards Institute (ETSI) [51]. Based on information like speed and position transmitted periodically either in Basic Safety Messages (BSMs) or in Cooperative Awareness Messages (CAMs), vehicles can determine dangerous situations and warn the driver accordingly. Such basic safety applications are also called *Day 1* or *cooperative awareness*. Minimal requirements for V2V safety were specified in SAE J2945 [54] in 2016. For a deeper understanding, several introductions to intelligent transport systems (ITSs) exist [30], [59]–[63]. Willke *et al.* [64] have surveyed V2X application classes, requirements, and communication protocols. Sawade and Radusch [65] have classified cooperative driver assistance systems according to their realizability with dedicated short-range communication (DSRC).

Subsequently, research about extending the range of communication within VANETs via intermediate vehicles emerged. This *cooperative routing* or *relaying* of messages helps disseminate information. Several survey papers [5], [66]–[69] give an overview on related literature. Dressler

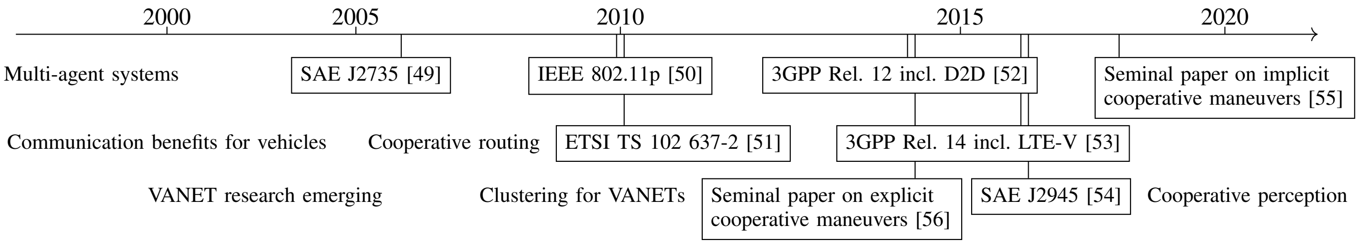


Fig. 1. Timeline including research fields and milestones (in boxes) regarding vehicular networks. While activities on V2X communication have a long history, cooperative maneuvers only recently started to be investigated in detail.

et al. [70] have classified broadcast protocols according to priority and area of delivery, reconciling different applications and use cases. Problems related to information dissemination are clustering vehicles [71], [72] and representing information, e.g., in information-centric networks (ICNs) [73], [74].

Platooning, or cooperative adaptive cruise control (CACC), gained attention in the early 2000s [75]. A chain of vehicles synchronizes lateral and longitudinal control to reduce inter-vehicle distances and thus fuel emissions. The research focus has been on platoon management procedures like joining, leaving, merging of platoons, stability analysis, and control. Jia *et al.* [17] have surveyed the related literature.

Since 2016, short-range "sidelink" direct communication called vehicular LTE (LTE-V) is included in Third Generation Partnership Project (3GPP)'s Release 14 [53] as an alternative to WiFi-based direct communication. Release 16 Fifth Generation Cellular Communication (5G) [76] will integrate short-range communication as a native component. In addition to the sidelink, network-based cellular communication also became a research topic. Original 3G was not able to fulfill the latency requirements of vehicular safety applications as well as DSRC [77]. For example, 3GPP specifies a V2V communication latency of less than $100\,\mathrm{ms}$, in certain cases of less than $20\,\mathrm{ms}$ [78]. Certain types of warnings, like local hazard or traffic jam warnings, can however be transported via cellular 3G/4G networks and are already deployed in series production vehicles. Networks combining multiple radio access technologys (RATs), called *Heterogeneous Networks* or *HetNets*, have been extensively surveyed [79]–[82]. Using multi-access edge computing (MEC) as powerful platform along the road can be beneficial for V2X applications [83]. Readers can find surveys on MEC in [84], [85].

B. Scope and Terminology

The previous section gave an overview of different vehicular communication and cooperation types, mainly from the physical to the network layer. In the future, communication will not be confined to broadcasting and routing cooperative awareness beacons. In contrast, the vision of cooperative, connected, and automated mobility (CCAM) states that automation, communication, and cooperation will coevolve, as displayed in Fig. 2.

As of today, *Day 1* applications are already realized: backend connectivity enables sharing information among vehicles, and advanced driver assistance systems (ADASs) are becoming more and more popular. However, these services are often not related to each other. For *Day 2*, sharing perceived objects or sensor data can work as input, enhancing environmental models for automated driving [86]–[91]. Starting from *Day 3*, even intentions are shared and coordinated. Connected and automated vehicles (CAVs) with a high automation state can use new communication technologies in order to improve cooperation [92]. In the end, a completely connected ecosystem will share perceptions and negotiate maneuvers to jointly optimize traffic flows and maximize safety.

To reach this connected ecosystem, it is of pivotal importance to be able to perform *cooperative maneuvers*, where automated vehicles negotiate on joint maneuvers, increasing joint utility (*Day 3/4* applications). This paper specifically considers cooperation between automated vehicles that can communicate intents and needs to other vehicles. Since development cycles for communication technology are short, we consider those cooperation aspects in a technology-neutral way but will mention technological aspects where needed. Regarding *cooperation*, we follow the definition by Norman [93] "to act with another or others for a common purpose and for common benefit," and by Burger *et al.* [94] "an action willingly and knowingly executed with the intention to work towards a common goal." Translated to vehicular cooperation, this means exchanging intents, costs, or other information and subsequently agreeing—implicitly or explicitly—on actions each vehicle should perform. To make this explicit, most studies regarding cooperative maneuvers treat only automated vehicles, assuming that human-driven vehicles do not exist any more, and they do not consider traffic infrastructure like traffic management systems interfering with the vehicles' intents. Those two topics require future research regarding the transition phase of mixed traffic and optimal traffic flows, as described in more detail in Section VI-B2.

Cooperation for crossing intersections is one specific subgroup of cooperative maneuvers for which extensive work has already been published. Centralized and decentralized approaches exist, some of which also involve traffic infrastructure. However, many studies mostly concentrate on the control aspects and do not propose concrete communication protocols for solving the challenge of intersection coordination. Most of the time, perfect reception and 100% cooperative vehicles are assumed. Regarding this specific topic, we refer the reader to existing surveys [7], [20], [21].

In our considerations, we have to define the term *cooperative maneuver* further. The atomic building block for maneuvers is an *action* of a single vehicle. Such actions comprise "staying in the current mobility state," but also changing

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

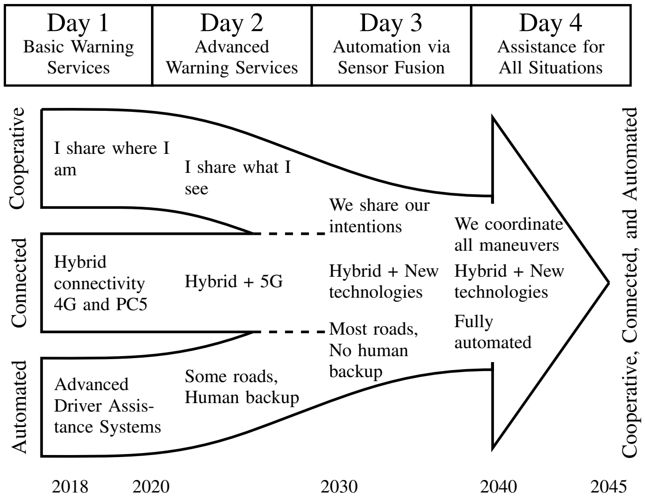


Fig. 2. Evolutionary path from basic use cases to full CCAM, as envisioned by the European Commission (EC) during the 2018 ITS World Congress [92]. "Cooperative" describes the cooperative actions taken, "Connected" describes foreseen communication technologies, and "Automated" describes what level and type of automation would be available and where.

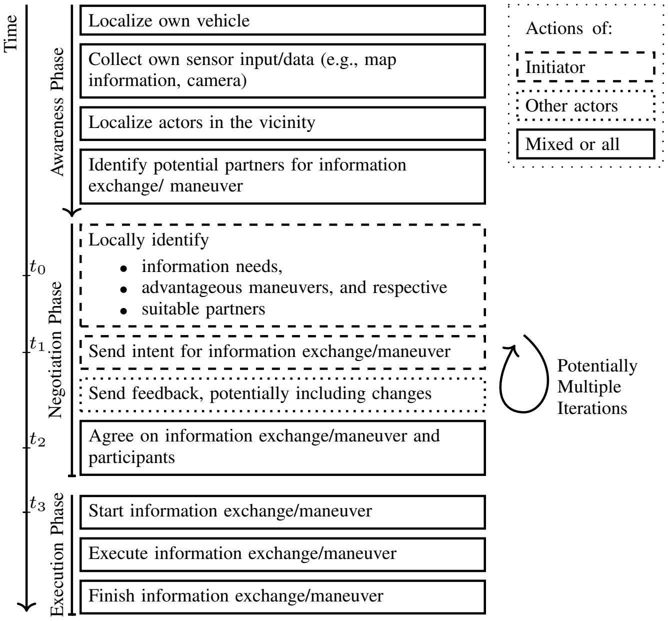


Fig. 3. Basic phases and related actions that have to happen for advanced vehicular cooperation. The arrow for the Awareness Phase symbolizes that this will continue throughout the whole cooperation for cross-checks and continuous evaluation of the situation. Solid boxes describe actions that are either done in parallel or jointly.

this mobility state, like accelerating, adjusting heading angle, or changing lane. A sequence of these actions, including the respective parameters like duration or target velocity, is called *maneuver* of a particular vehicle. Lastly, *cooperative maneuvers* involve at least two vehicles who have to perform at least one action each, without them all being "stay in the current mobility state." The sole exchange of information does not classify as a maneuver since there are no driving actions involved. For example, an automated vehicle could describe a cooperative overtake as a joint maneuver consisting of "overtake" for vehicle A and "stay in current mobility state" for vehicle B. However, the actions, maneuvers, or cooperative maneuvers do not need to be stated explicitly. For example, if trajectories are shared, a lane change may be expressed by waypoints that lead to an adjacent lane. The message exchange that enables cooperative maneuvers will be called *cooperation protocol*.

For communication-based vehicular cooperation of *Day 2* and beyond, we identified several phases. We distinguish between an *Awareness*, a *Negotiation*, and an *Execution Phase*, see Fig. 3. First, vehicles have to become self-aware (e.g., in terms of self-localization) and aware of others (e.g., via onboard sensors). Based on the V2X signals received, they can identify possible communication partners for cooperative perception and maneuvering. When they have detected a need or opportunity for cooperation (at time t_0), a negotiation is initiated (t_1): it is the initiator's goal to fulfill its needs through cooperation. Since this may induce effort for the others, the participants need to find a trade-off found cooperatively via implicit or explicit feedback sent to the initiator. After potentially several rounds of intent exchange and feedback, an agreement is reached at time t_2. If the outcome is to cooperate, then execution of the information exchange or cooperative maneuver will start at time t_3.

When denoting different vehicles in an interaction, the initiating one will also be called host vehicle (HV) or *ego vehicle*, and others are termed remote vehicles (RVs). The HV and RVs communicate via V2X, which can be distinguished based on the air interface used. For communication over 3G, 4G, or 5G networks, the term "Uu" interface is used. In contrast, direct communication among actors happens on the sidelink or "PC5" interface.

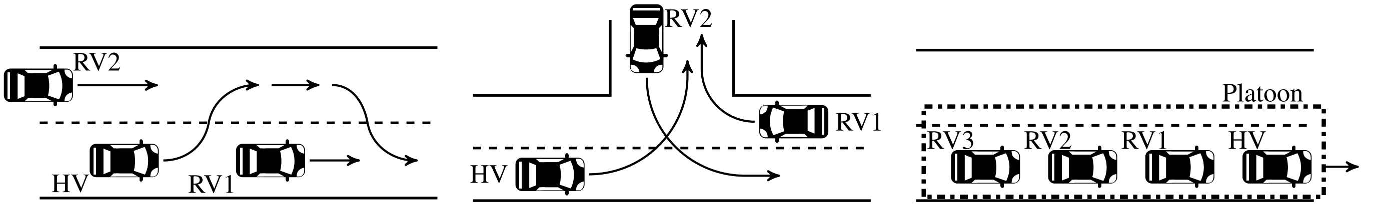
For a clearer picture for the types of interactions we subsume under the term *cooperative maneuver*, Fig. 4 depicts several use cases. The most archetypal application is a cooperative lane change or overtake (see, e.g., [56]), in which an HV wants to overtake at least one RV, engaging in interaction with it on the specifics of the planned overtake. Another use case is an uncontrolled intersection [95], where automated vehicles—potentially with the help of traffic infrastructure—negotiate and decide in which order they will cross the intersection. While not the focus of this survey, some of the protocols mentioned in Section IV also enable coordination at intersections. Lastly, platooning or CACC is a cooperative maneuver. Here, vehicles driving behind each other will tightly align their trajectories, enabling shorter safety distances, reducing aerodynamic resistance. As mentioned earlier, several earlier surveys cover different aspects of platooning [17], [18] and we thus do not include this special use case in this survey.

The three mentioned use cases are only examples out of a variety of potential scenarios for cooperative maneuvers. Later in this text, we use the terms "use case," "scenario," and "application" interchangeably.

III. ARCHITECTURES FOR COOPERATIVE MANEUVERS

For the advanced use scenarios outlined in the following sections, several different architectures have been envisioned.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials



(a) Cooperative overtake, which can involve overtaking, overtaken, and surrounding vehicles.

(b) Cooperative intersection crossing, where the HV can optimize traffic flow by letting RV2 pass first, in parallel to RV1.

(c) Platooning, where several trailer vehicles are lead by a tractor vehicle.

Fig. 4. Some use scenarios involving cooperative maneuvers. Sharing intents and cooperatively increasing total utility can be beneficial in a wide range of situations. Arrows denote current intents.

Here, the *communication* or *information dissemination* architecture, the *computation* architecture, and the *decision-making* architecture can be distinguished. All of them can be classified into a spectrum between *decentralized* among traffic participants, and *centralized*. Table II summarizes the relevant papers of this section.

A. Communication

Historically, publications on communication architectures for VANETs proposed either hybrid architectures combining cellular and direct communication technologies [96], [97], [99] or they dealt with a mediation between different direct communication technologies [100], [101]. However, these architectures mainly focus on data dissemination for basic warnings or cooperative awareness messages, without considering advanced use cases. Thus, they will not be the focus of this section, since we are concerned about architectures enabling cooperative maneuvering.

1) Decentralized: In a decentralized case, traffic participants will be more or less equal entities and mainly broadcast information like intents, see Fig. 5a. A central entity like a group leader or roadside infrastructure is not necessary for routing information [107].

2) Among Groups: On the other hand, communication and information dissemination could also happen among groups of vehicles [102], see Fig. 5b. This would involve extensive information sharing among group members but may lead to inefficiencies at group boundaries [55]. Besides, there are still open questions on whether or not, and if yes, how group leads should be elected to allow for stable groups.

3) Centralized: The last approach is to completely disseminate information via centralized infrastructure along the road, as depicted in Fig. 5c. This has the advantage that as long as every traffic participant can communicate with the road side units (RSUs), even different communication technologies can coexist, mediated through the RSUs. However, one disadvantage of this is that vehicles have to entirely rely on the traffic infrastructure's availability, which can be very costly and would take extra time for buildup.

Research suggests that the superior option for safety communications are hybrid communication architectures [98], [99]. For cooperative maneuvers, such an architecture would mean that vehicles can coordinate among themselves, and centralized entities (like MEC servers) are also capable of sending proposals to (groups of) vehicles. However, the coexistence of different communication technologies is an open issue. This is true for different air interfaces [99], but also within the same type of air interface. For direct communication, mainly two technologies and their technological improvements are under discussion: Institute of Electrical and Electronics Engineers (IEEE) 802.11p-based DSRC or ITS-G5 as well as LTE-V have both been developed for basic warning services. Current development for the successor technologies IEEE 802.11bd [108] and 5G-V2X is targeting advanced use cases like sensor sharing or cooperative maneuvering, demanding for more stringent requirements on latency and others [22], [103]. 3GPP suggests transmission latencies below 3 ms within a communication range of 500 m and with reliabilities of up to 99.999% [109] for the case of cooperative emergency trajectory alignment. It is currently unclear which technology combination is the best fit for vehicular networks [23] or if such an optimal technology can be identified.

B. Computation

For advanced vehicular cooperation, computation is a crucial element. For cooperative maneuvering, maneuver calculation and the processing of different options reacting to proposals of other vehicles need the most computational effort. Decentralized computation can be distinguished from a centralized one.

1) Decentralized: In a decentralized approach, every vehicle computes only its own next maneuver and processes incoming requests, as depicted in Fig. 6a. Participants may need to exchange information first. Afterward, negotiation and finding trade-offs can be necessary whenever planned maneuvers interfere with each other. Such coordination can, for example, happen using distributed control [104], [110] or maneuver negotiation [107].

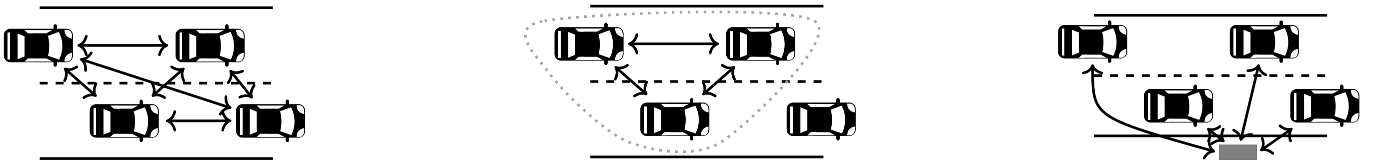
Regarding the software architecture deployed on vehicles, research goes back to 2000 [105]. Most of the architectures are implementation-specific. Therefore we did not include a separate section on them in this paper. Instead, we have derived general functional blocks from the surveyed studies that are needed for cooperative automated driving, as depicted in Fig. 7:

Each vehicle will need a compute function that evaluates incoming requests for cooperation regarding their feasibility and costs to decide on acceptance or rejection (*Cooperation*

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

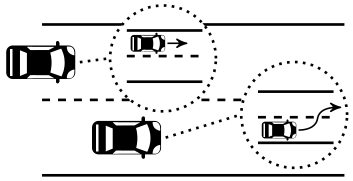
TABLE II
SUMMARY OF THE SURVEYED PAPERS RELATED TO ARCHITECTURES

Study	Year	Summary
Communication Architectures		
Kato *et al.* [96]	2013	Architecture including LTE to augment DSRC-only deployments for periodic messages.
Zhang *et al.* [97]	2015	Coexistence of Wi-Fi and cellular via 'almost blank subframe' scheme mitigating co-channel interference.
Taleb and Benslimane [98]	2010	Combination of DSRC and 3G including gateway selection scheme, enhancing PDR.
Dreyer *et al.* [99]	2016	A RAT selection algorithm for vehicles equipped with DSRC and LTE, improving channel load.
Abbas *et al.* [100]	2019	Analytical evaluation of a hybrid architecture of DSRC and V2N to deliver packets to other vehicles.
King *et al.* [101]	2018	Safety message protocol translator for vehicles with only LTE-V or DSRC.
Frese *et al.* [102]	2007	Investigating distributed, self-organized establishment of cooperative groups based on distance.
Naik *et al.* [22]	2019	Standardization of 802.11bd and 5G-V2X, focusing on physical and MAC layers.
Zeadally *et al.* [103]	2020	Standardization of DSRC and C-V2X, concentrating on physical and MAC layers.
Anwar *et al.* [23]	2019	Comparison of 802.11bd and 5G-V2X to each other and their predecessor in terms of latency, data rate, and PER.
Computation Architectures		
Qian *et al.* [104]	2016	Design a model predictive control (MPC) framework for trajectory generation of vehicle formations.
Tsugawa *et al.* [105]	2000	Control architecture for automated vehicles: vehicle control, vehicle management, and traffic management layer.
Lee *et al.* [106]	2019	Trajectory-aware edge node clustering scheme to minimize service delay between edge nodes.
Decision-Making		
Bali *et al.* [71]	2014	Taxonomy for vehicle clustering and analysis of existing protocols.
Cooper *et al.* [72]	2017	Survey of clustering techniques like cluster head selection, member affiliation, and cluster maintenance.

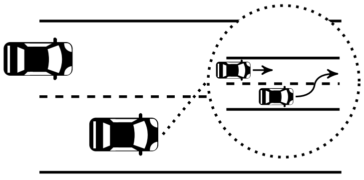


(a) Decentralized. (b) Among a cooperative group (enclosed in dotted line). (c) Centralized via roadside infrastructure (gray box).

Fig. 5. Illustration of different communication architectures. The degree of centrality of vehicular communication determines how information like intents is distributed among the participating vehicles in a cooperative maneuver.



(a) Decentralized.



(b) Centralized.

Fig. 6. Illustration of different computation architectures. An entity can (a) compute exactly its own maneuver, or (b) design the cooperative maneuver including all foreseen participants.

Logic). The *Application Logic* detects cooperative maneuver opportunities and evaluates whether they are worth driving. The *Message Service* is responsible for routing incoming V2X messages to the respective functional blocks and for managing transmission of messages. Since vehicles may be equipped with different capabilities, this function should best be present on the vehicles themselves. This also has the advantage that software updates can be performed in a distributed fashion, for example, when the vehicles are parked. Otherwise, the central system would have to be updated, potentially causing a service outage during the update. The *Motion Planning* derives the trajectories a vehicle will follow. It can be divided into strategic (decision on trip route), tactical (handling a specific traffic situation), and control level (actual control over actuators in the vehicle) planning [111]. Whenever any of the functions mentioned above are externalized, e.g., to an edge server, an additional verification module needs to check whether the received trajectory or maneuver is acceptable, for safety and liability reasons. Lastly, the sensors and actuators are deployed within each vehicle, while additional sensors may be deployed along the road.

2) Centralized: In the centralized case, one entity will compute maneuvers for more than one vehicle, as depicted in Fig. 6b.

A locally-centralized computation is happening if one vehicle determines a cooperative maneuver also involving surrounding vehicles. An advantage of such a design is that vehicles can more reliably predict the future behavior of other

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

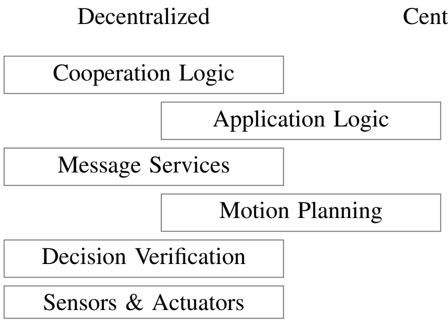


Fig. 7. High-level functional blocks necessary for cooperative automated maneuvering. Most modules are foreseen to be deployed on the vehicles themselves, but the application logic and motion planning may be partially centralized.

traffic participants since these may choose to follow the actions designed for them.

Depending on the area covered and the number of actors involved, the computation can be more centralized: on road (segment), district, or even city level. Here, an edge server may take all involved vehicles' trajectories, intents, and capabilities into account to compute where trajectory changes may be necessary and then distributes these trajectories to vehicles. Such an approach is pursued—on a small scale—by Sequeira *et al.* [112]. One advantage is the higher computational performance of the server, which vehicles or city infrastructure can use to find better solutions to the "global" optimization of, e.g., traffic efficiency. Lee *et al.* [106] developed a trajectory-aware edge node clustering scheme, optimizing pro-active service information provisioning in order to minimize service delay between edge nodes. Preparing service information in advance could, for example, enable more efficient sensor sharing across edge servers. In the case of centralized computation, vehicles need to be able to trust the central management entity that the trajectories are well suited and that neither devices nor communication has been tampered with.

Only a few studies have been published that describe hardware requirements for cooperative maneuvers. Lehmann *et al.* [55] state they use an Intel Core i7-6820HQ as CPU, and even with this hardware from 2015, it was possible to evaluate and negotiate trajectories within a few milliseconds. This may indicate that future hardware used for automated vehicles will easily fulfill the requirements that the different modules in Fig. 7 pose on onboard hardware. However, this point has to be addressed by future research, as detailed in Section VI-C5.

C. Decision-Making

How and where to make driving and cooperation decisions is at the heart of cooperative maneuvering. Vehicles have to decide on the own route, on cooperative maneuvers to perform, and on responses to others' intents. Specific timing requirements result depending on the mechanism employed. In general, finding a potential maneuver should happen before the traffic situation has changed too much for the maneuver to be still feasible. This time window depends on factors like the maneuver to agree on, the relative velocities, and the number of participants involved.

As decision-making stretches over the negotiation phase as depicted in Fig. 3, the relevant time covered is from t_0 (time of identification of a need/opportunity for a cooperative maneuver) until t_2 (agreement on cooperative maneuver). Independent of the protocol used or decision-making approach taken, it is critical that the duration of negotiation $t_{\text{neg}} = t_2 - t_1$ is short enough that the traffic situation does not change considerably. The suitable length of this time interval depends, among others, on relative velocities, time until t_3 (start of the cooperative maneuver), and the maneuver negotiated. Considering human drivers in normal, non-emergency driving situations, t_3 usually follows after t_0 within the range of a few seconds.

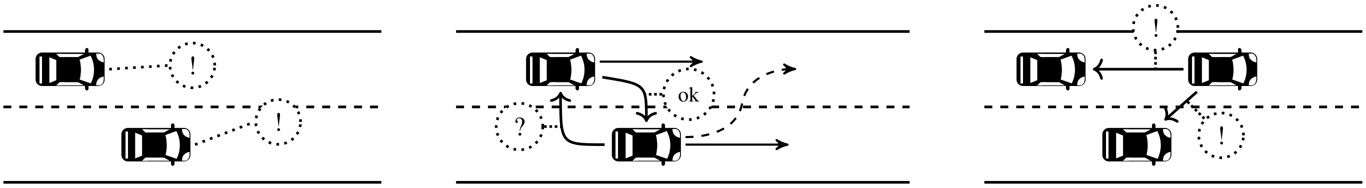
1) Independent Decisions After Information Exchange: The first option is the "most decentralized" one, see also Fig. 8a: after mutual information exchange, decisions are made independently on each vehicle. Based on the information received, models for others' movements can be improved, and sensor vision can be enlarged. The only requirement for this type of application is *interoperability* since traffic participants have to understand the information shared by others. Consensus on decisions is not needed since vehicles plan and execute trajectories independently according to their local motion planning unit; communication is only used for augmenting the information available (see [110], [113], [114] as discussed in Section IV).

Time planning is flexible since the algorithms on the individual vehicles can derive trajectory adjustments and other changes in planned maneuvers in their own timing. They use communication merely to update the environment model as a basis for decisions. This means that after identification of a maneuver opportunity (t_0), there is no need to send out intents (t_1) or agree on cooperation with others (t_2). The maneuver can directly start whenever the actor sees fit (t_3).

2) Requests and Reactions: In this second class of approaches, depicted in Fig. 8b, we can distinguish *initiators*, or *requesters*, and *participants*, or *providers*. A vehicle detecting a need (at t_0 in Fig. 3), be it for information such as detected objects or for a certain maneuver like a lane change, will send out a request to others (t_1). It can share the vehicle's own need or intent with others or even include suggestions for the other participants. The other traffic participants then have to evaluate the request to determine whether it is possible to cooperate or not. They will inform the initiator of a positive or negative assessment, reaching t_2 and agreeing on the cooperative maneuver in the former case.

In the first version, vehicles only send their own intents or needs. For joint maneuvers, this means a feasible own driving strategy needs to be found by the participants, which enables the requester to perform the desired maneuver (see [107], [115] as discussed in Section IV). A drawback here is that vehicles cannot accurately predict the reactions of other participants in the case that the initiator's request is accepted. Requesters can try to guess others' most likely behavior according to own models, but since the control algorithms on other vehicles may differ, other trajectories than expected may be followed.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials



(a) Independent decisions after information exchange.

(b) Requests and reactions; arrows with broad tips denote communication, narrow tips indicate trajectories.

(c) Centralized.

Fig. 8. Illustration of different decision-making architectures. With how much authority other vehicles are involved in the ego vehicle's decision on which driving action to perform can range from (a) no direct authority, via (b) as negotiation partners, to (c) fully taking over the decision. Question marks indicate requests, exclamation marks indicate decisions taken or communicated.

In the second variant, the proposal of the requesting vehicle (at t_1) also includes suggestions for other vehicles' behaviors. This suggestion comes with the advantage that other vehicles only have to evaluate a proposal instead of finding a suitable maneuver by themselves, i.e., less computational extra load for vehicles that most likely do not experience any advantage from cooperation. This may shorten the time until reaching t_2, even if dedicated studies still have to show this. Besides, the initiating vehicle will know what reaction to expect from the others according to the agreed plan.

In some protocols [116], [117], vehicles can even negotiate such proposals for others' actions or roles. RVs can suggest alternatives that the HV will then evaluate. Potentially after several rounds of negotiations among the involved vehicles, the maneuvers should converge to a plan acceptable for all, and a cooperative maneuver can begin. It has to be assured, though, that the maneuver participants reach t_2 sufficiently fast.

This approach makes it possible to meet demands as needed, as opposed to periodic, situation-independent broadcasts. In the request-response approach, even infrastructure like RSUs or MEC platforms can derive proposals on the subsequent actions and distribute them to relevant vehicles. Infrastructure involvement has the advantage that MEC servers usually are computationally much more powerful and less resource-constrained than vehicular computing platforms.

3) Centralized: In centralized architectures, a central unit makes decisions on maneuvers. Examples are infrastructure nodes like an RSU or a MEC servers or group leader vehicles, e.g., a platoon head. Vehicles could dynamically elect such group leaders for a specific period, but related issues, including redundancy, leader election, and consensus mechanisms, are beyond the scope of this paper.

In the case that one vehicle decides for others, as seen in Fig. 8c, vehicles have to form a group or cluster and decide on a trustworthy group leader. This act would authorize the group leader to make decisions on behalf of other vehicles, except for situations where an emergency maneuver has to be executed. The proposals of the group lead would still be monitored and checked by the individual vehicles in order to ensure their own safety. Several studies focus on algorithms and protocols for forming such groups for traditional VANETs, see for example [71], [72] and the references therein.

If infrastructure is making the decision instead, it can be used in several ways. First, equipped with high authority, a MEC node may propose mandatory maneuvers to vehicles. Based on its usually higher computational power, the infrastructure may optimize traffic even on a larger scale than single vehicles. This optimization would have to be combined with compulsorily following the proposals without renegotiation. Here, making sure that the infrastructure is not tampered with and malicious is very important. Another option is that infrastructure can advise vehicles without being able to force them (see [118] as discussed in Section IV), similar to what we discussed in the previous section.

IV. COOPERATIVE MANEUVERS

Vehicles—mostly automated ones—will communicate to coordinate maneuvers. This communication includes transmitting intents and maneuver proposals, a joint — distributed or centralized — evaluation, and procedures for negotiating and agreeing on coordinated maneuvers. This chapter summarizes and classifies approaches for enabling cooperative maneuvers among vehicles, giving a short overview on papers in Table III.

A. Approaches

Various approaches have been proposed in the literature that broadly belong to one of three categories: first, maneuvers can be implicitly understood from communicating the ego vehicle's intent, for example, trajectories. Others, also sharing their intents, can signal cooperation implicitly via changes in these intents, for example, updated trajectories. Second, vehicles can announce and negotiate maneuvers. Here, the main difference is that the intents communicated by the first vehicle, e.g., a trajectory or a maneuver, are explicitly accepted by other vehicles. In a third approach, emergent cooperation can happen without communication via predefined templates or control logic installed in every vehicle. At the end of each subsection, we highlight noteworthy contributions among the surveyed papers.

1) Implicit: This class of approaches was initially proposed by Lehmann *et al.* as Maneuver Coordination Service (MCS), based on sharing *planned* and *desired* trajectories [55]. Noting that studies had only proposed application-specific protocols for cooperative maneuvers, they designed a generic approach. Vehicles periodically broadcast their planned trajectories. Once a vehicle wants to change its planned trajectory, for example, when performing a lane change, it sends out the desired trajectory along with the planned one. Other vehicles whose

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

TABLE III
SUMMARY OF STUDIES ON COOPERATIVE MANEUVERS

Study	Year	Summary
Approaches		
Implicit (Section IV-A1)		
Lehmann *et al.* [55]	2018	Cooperative maneuvering based on periodic broadcast of current *planned* and *desired* trajectory.
Correa *et al.* [118]	2019	Enable RSUs to propose maneuvers, speeds, etc. for vehicles; based on the approach presented in [55].
Llatser *et al.* [107]	2019	Extend the approach of [55] to include costs along with several planned and desired trajectories.
Kessler/Knoll [119]	2019	Broadcast maneuver options and costs, use mixed-integer linear programming for optimization.
Düring/Pascheka [114], [120]	2014f	Cooperative maneuvering via exchange of maneuver options and costs, introducing a "memory of costs."
Moradi-Pari *et al.* [110]	2017	Exchange model parameters to improve prediction of other vehicles' movements.
Explicit (Section IV-A2)		
Franke *et al.* [121]	2014	Vehicles reach a common environmental model, then exchange cooperation offers among each other.
Hobert *et al.* [56]	2015	Enable cooperative lane change (CLC) via a request-response scheme for finding suitable partners.
Aoki/Rajkumar [122]	2017	Design a coordination protocol for lane merges among autonomous vehicles.
An/Jung [123]	2018	Enable CLC via requests containing a sampled lane change trajectory with binary reject/accept responses.
Heß *et al.* [115], [124]	2018f	Cooperative maneuvering based on reservation of road space.
Sawade *et al.* [116]	2018	Cooperative maneuvering via negotiation of functions and roles, focusing on robustness.
Xu *et al.* [125]	2019	Adapt [55] to include *request*, *promise*, and *confirm* messages for negotiation of desired trajectories.
Maksimovski *et al.* [126]	2021	Adapt [55] to 12 subtypes of MCMs with different priorities.
Häfner *et al.* [117]	2020	Cooperative maneuvering and information exchange based on generic requests and responses.
Emergent (Section IV-A3)		
Schwarting/Pascheka [127]	2014	Prediction of other vehicles' behavior, then resolving all predicted conflicts based on a cost function.
Lenz *et al.* [128]	2016	Cooperative motion planning based on Monte Carlo Tree Search using a cooperative cost function.
Manzinger *et al.* [113]	2017	Increasing efficiency of motion planning algorithms by maneuver templates for emergency situations.
Peng/Tomizuka [129]	2018	Control algorithm for mixed human-automated vehicle traffic using MPC with persuasion and concession.
Planning of Cooperative Maneuvers (Section IV-C)		
Burger/Lauer [130]	2018	Generation of optimal trajectories based on mixed integer quadratic programming.
Graf *et al.* [131]	2019	Single-vehicle trajectory planning for overtaking on highways.
Huang *et al.* [132]	2019	Platoon controller combining discrete cooperative maneuver switching and continuous motion control.
Li *et al.* [133]	2017	Centralized controller for multiple vehicle CLCs involving standard formations and look-up tables.

planned trajectory intersects with the initiator's desired trajectory can then evaluate whether they can adjust their own planned trajectory to enable the initiator to change its plan. If this is possible, they adjust their planned trajectory; and once no planned trajectories intersect with the new desired trajectory, the initiator can make its desired trajectory its new planned one. A challenge of this approach is the possibility for other vehicles to trigger cascading processes to make the desired trajectory possible, potentially leading to high latencies before the initiating vehicle knows whether its maneuver is viable.

Within the TransAID project, Correa *et al.* [118] extend Lehmann *et al.*'s protocol to make it possible for infrastructure like RSUs to control traffic in a centralized manner. The infrastructure proposes maneuvers via the MCM. In its *VehicleManeuverContainer*, vehicles can include planned and desired trajectories, while RSUs can suggest speeds, lane changes, or automation state changes to vehicles.

In the IMAGinE project, Llatser *et al.* [107] adjust Lehmann *et al.*'s approach differently by also introducing an MCM format. In their distributed design, the MCM contains not only trajectories but also associated costs, and vehicles send it themselves. Another adaption is that vehicles can share several alternatives and desired trajectories besides one planned one. This gives receiving vehicles a better understanding of the costs related to different maneuver options foreseen by the sending vehicle. In their approach, these MCMs are also sent periodically.

Another class of implicit approaches is based on the broadcast of information about vehicles such that every vehicle in the vicinity has the same knowledge about specific parameters.

In Kessler and Knoll's [119] approach, vehicles share motion options and associated costs. Unconnected vehicles' intentions are estimated locally. Subsequently, each vehicle searches for the maneuver combination minimizing total costs and follows the calculated trajectory for itself. The only communication related to complex maneuvers evident from their work are maneuver options and costs that vehicles broadcast every time intents, i.e., costs associated with certain motion options, change. The difference to Llatser *et al.* [107] is twofold: first, there is no discrimination between planned, desired, or alternative trajectories. Second, vehicles do not share, e.g., changed planned trajectories to signal cooperation, but rather every vehicle optimizes total costs, and vehicles follow their calculated best trajectory independently. Their approach mitigates the disconnect between strategical driving decisions and actual maneuver control that is sometimes present in automated driving algorithms by integrating both into a "behavior coordination" module.

Like Kessler and Knoll, Düring and Pascheka [114] present a distributed algorithm to determine an optimal maneuver combination based on costs for maneuver primitives: lane keeping and lane changes are parametrized via polynomial coefficients. Vehicles share possible maneuvers with others together with the associated costs. Every agent then calculates the optimal, collision-free maneuver based on total costs independently. However, their algorithm checks every possible maneuver combination at every agent and is thus not real-time capable for larger systems. In an extension of their work [120], they have introduced a memory of costs to introduce fairness into their system.

Independence of vehicles is also important in Moradi-Pari *et al.*'s [110] approach. They use Auto Regressive-Exogenous (ARX) models for small-scale structures of vehicle dynamics like deceleration or acceleration. The respective model parameters for the current driving state are estimated by each vehicle and then broadcasted to surrounding vehicles in order for them to predict the respective movements more accurately. On the other hand, each vehicle can perform an own maneuver based on these predictions of others.

Prominent contributions: Lehmann *et al.* [55] were the first to present a general, implicit way of coordinating cooperative maneuvers. They did, however, not include a quantitative evaluation of their proposal. While use cases like cooperative intersection crossing have been investigated in research earlier, Correa *et al.* [118] were the first ones who extended general cooperative maneuvers to traffic infrastructure. Regarding evaluation, Kessler and Knoll [119] introduce the ratio of participants' maneuvers' costs as a measure of fairness. This ratio could become one of several metrics for judging cooperative maneuvers.

2) Explicit: Franke *et al.* [121] designed a protocol for collective scene description combined with cooperative maneuvering among automated vehicles. To this end, they proposed a cooperative driver assistance system (CDAS) protocol based on an exchange regarding the vehicles' ego states as well as perceived static and dynamic objects. Beyond the contents of CAMs, they propose to share the objectives and hard and soft constraints of each vehicle. After a vehicle determines a conflict, it sends a *Request for Cooperation Message* (RCM). Other vehicles can support building a collective scene description in the modeling phase, even though the authors do not specify how to determine which information is helpful or what gets shared by whom. Next, every vehicle calculates possible offers for cooperation and sends an *Offer for Cooperation Message* (OCM) such that other vehicles can evaluate all other offers. After each vehicle has shared its evaluation via an *Evaluation of Cooperation Message* (ECM), every vehicle calculates the best alternative and sends an *Accept Cooperation Message* (ACM). If a vehicle has not performed the evaluation itself, it has to cross-check the proposed cooperation with its own constraints and then send a *Confirmation of Cooperation Message* (CCM). In the following acting phase, vehicles used their local controllers for carrying out the maneuvers. Meanwhile, *Status of Cooperation Messages* (SCMs) can be used to adjust or replan the maneuver [121]. We exemplarily display their message flow in Fig. 9. They did not include a quantitative analysis in their publication, but it seems that the exchange and feasibility check of every OCM with and by every vehicle puts a heavy burden on the network as well as the computing platforms in the vehicles.

Heß *et al.* [124] present an independent approach building upon space-time reservation. When vehicles try to change lanes or collisions are foreseen, they trigger a reservation procedure for a certain part of the road track. This road area may be static or even moving. The initiating vehicle sends a *request* for its desired road space, and surrounding vehicles may send a *commit* to express support for the reservation. In the case that they refuse the reservation, no response is sent. If not all vehicles considered necessary respond in time, the initiating vehicle will not enter the road area it tried to reserve. In every negotiation round, participants can only exchange one *request* and several *commits*, and all communication and negotiation happen between the initiator and respective surrounding vehicles. They show the real-time performance of their protocol by experiments and real-time simulations, demonstrating that it is possible to reserve lane space and negotiate for its usage [115].

Sawade *et al.* [116] developed their collaborative maneuver protocol (CMP) with a focus on robustness. Maneuvers are negotiated using a request-response scheme combined with a heartbeat for synchronization. Describing maneuvers based on functions and roles (e.g., *leader*, *follower*), they avoid trajectories that would lead to frequent cancellations due to deviations.

Xu *et al.* [125] concretized and extended Lehmann *et al.*'s implicit approach [55] and made it explicit. Besides periodic transmission of planned trajectories, they designed a request-response scheme for maneuver negotiation. The initiator transmits a *request* including the desired trajectory. Other vehicles can answer by a *promise* to take one of several included, i.e., offered, trajectories. From those answers, the initiating vehicle will try to devise a conflict-free cooperative maneuver and, if found, send it to the other vehicles via a *confirm* message. They mention that these three messages are also sent periodically.

Maksimovski *et al.* [126] extend the same approach [55] in another way, namely by adding priority levels to different subtypes of MCMs. With increasing criticality level, vehicles receiving an intent shall be more inclined to accept and accommodate for another vehicle's desired plan changes. They do not describe how such an analysis or trade-off of interests may work.

In order to provide a possibility to negotiate maneuvers not only for the initiating vehicle but also for an ensemble of participating vehicles, we developed the Complex Vehicular Interactions Protocol (CVIP) [117]. It is based on the idea that the initiating vehicle designs maneuvers for all relevant, involved vehicles. These are put together as *Maneuver Containers* including the actions, the respective actors, as well as relative or absolute timing and other information. The vehicle then sends these containers in a *Cooperative Request Message* (CQM) to others, who have to evaluate the proposal instead of designing trajectories on their own and checking them, effectively reducing computing effort at remote vehicles. Their feedback, which can be simple acceptance or requests for changes, are sent in a *Cooperative Response Message* (CRM). Such negotiation goes on until a sent request is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

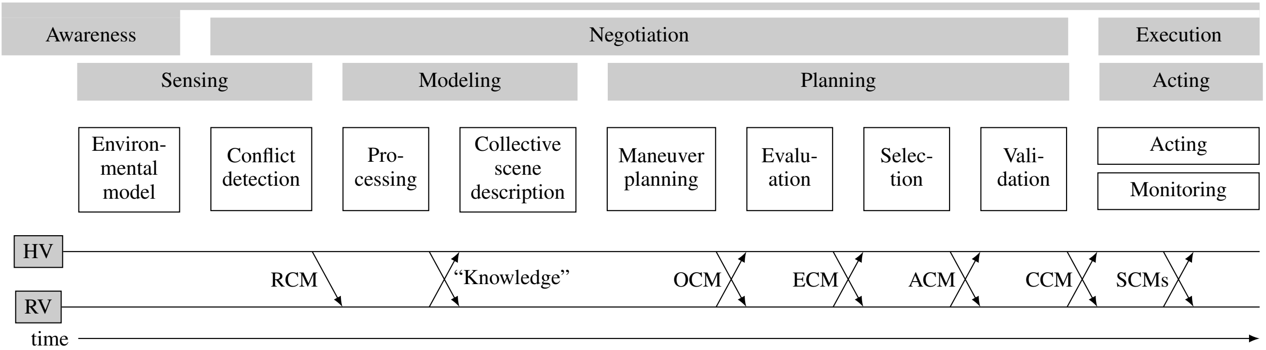


Fig. 9. Exemplary message flow of the cooperation protocol used by Franke *et al.* [121]. The white boxes describe functions executed by the involved vehicles. The gray boxes above depict phases as envisioned by Franke *et al.* based on [134] (lower row) and according to Fig. 3 (upper row).

TABLE IV
COMPARISON OF SPECIFIC ASPECTS AND ARCHITECTURE OPTIONS OF EACH PROTOCOL

Protocol/ Message	Year	Predictability of others' reactions	Distribution of computational load	Communication	Computation	Decision-making
Implicit protocols						
Vehicle models [110]	2017	✗	Equally distributed	Decentr.	Decentr.	Independ.
MCS (implicit) [55], [107], [118]	2018+	✗	HV calculates desired trajectory, RVs design reactions	Decentr.	Decentr.	Req. & React.
Motion options and costs [119]	2019	(✓) (costs)	Equally distributed	Decentr.	Decentr.	Independ.
Maneuver primitives and costs [114], [120]	2014+	(✓) (costs)	Equally distributed	Decentr.	Decentr.	Independ.
Explicit protocols						
CDAS [121]	2014	(✓) (constraints & objectives)	HV triggering, then negotiation	Groups	Decentr.	Req. & React.
Merging [122]	2017	✗	HV proposes, RVs react	Groups	Decentralized	Req. & React.
Space-time reservation [115], [124]	2018+	✓ (✗ if only own road space is reserved)	HV calculates desired trajectory, RVs design reactions	Central.	Central. or Decentr.	Req. & React.
CMP [116]	2018	(✓) (negotiated roles)	HV proposes, all evaluate	Groups	Central.	Req. & React.
MCS (explicit) [125], [126]	2019	✓ (chosen trajectory)	HV calculates desired trajectory, RVs design reactions	Groups	Decentr.	Req. & React.
CVIP [117]	2020	✓ (agreed maneuver)	HV proposes, all evaluate	Groups	Central.	Req. & React.
CLCS [56]	2015	(✓) (CLCS protocol)	HV proposes, RVs react	Groups	Decentral.	Req. & React.
CLC [123]	2018	✗	HV proposes, all evaluate	Groups	Decentral.	Req. & React.

accepted without changes by every involved vehicle. In this case, maneuver execution is initiated via a *Maneuver Status Message* (MSM) comprising all planned actions together with their current status, `Planned`. This and all other MSMs are confirmed by a *Maneuver Feedback Message* (MFM) from each receiving vehicle. Subsequently, whenever a vehicle changes a maneuver's execution status, this vehicle sends out a respective MSM to update all others on the changed status. Possible statuses comprise `Planned`, `inProgress`, `Finished`, or `Cancelled`.

Apart from these general approaches, several studies have designed application-specific, explicit protocols. Hobert *et al.* [56] have designed a CLCS. In the initial *Search Phase*, a vehicle trying to change lanes broadcasts a *Lane Change Request*, which vehicles willing to help answer by a unicast *Lane Change Response*. Based on the received answers, the initiator selects and announces a suitable partner. Once this matching has finished, the partnering vehicle enters the *Preparation Phase*, opening a gap and adjusting its speed. When finished, it sends out a *Lane Change Prepared* message. Following this, the *Execution Phase* is entered, where no communication occurs.

Aoki and Rajkumar [122] have designed the Autonomous Vehicle Protocol for Merge Points, enabling vehicles on low-priority lanes to merge onto high-priority lanes. It involves up to ten different messages like *enter*, *exit*, and *yield*. In mixed traffic, vehicles only use onboard sensors, while autonomous vehicles also employ communication to coordinate. Via traffic simulation, they confirm that their protocol improves traffic flow when compared to first-in-first-out or purely priority-based merging.

An and Jung [123] designed a different approach for a cooperative lane change (CLC). When the V2V communication module receives a lane change trajectory from the local planning module, it triggers a cooperative lane change. It samples the trajectory and sends the position and heading

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

angles at n discrete time steps in a *Lane Change Request* message, together with information like an identifier and the initiating vehicle's dimensions. When other vehicles receive such a request, they will evaluate the risk of collision and send out positive or negative responses. If no negative responses are received, the HV will proceed with the lane change. In any case, the HV confirms the reception of the response via another acknowledgment packet.

Prominent contributions: Hess *et al.* [124] wrote one of only a few papers that included real-life experiments, showing applicability on actual vehicles. This is the test that every cooperative maneuver approach will have to pass to be suitable for mass deployment. Xu *et al.* [125] compare their approach with uncooperative benchmark scenarios and thus quantify the benefit of cooperation for automated vehicles. These different evaluation methodologies show that a standard set of metrics for comparison of cooperative maneuvers is still missing; see also Section VI-C5.

3) Emergent: The last class of approaches does not use inter-vehicle communication, but cooperation is an emergent result of collective behavior. Lenz *et al.* [128] have designed a cooperative motion planning algorithm without inter-vehicle communication, based on Monte Carlo tree search using a cooperative cost function. Each vehicle tries to minimize its own cost function, consisting of weighted terms for performing lane changes, differing from desired speed, accelerating, or distances from objects. Under the assumption that other vehicles also search for minimal cost maneuvers based on their cost functions, vehicles autonomously find a motion to perform. Since other vehicles' cost terms are only estimated, vehicles monitor and account for deviations from expected behaviors. Schwarting and Pascheka [127] present a similar approach, minimizing a cost function based on predicted actions of other vehicles and pairwise evaluation of related costs for highway scenarios.

Manzinger *et al.* [113] focus on emergencies and propose a different approach. They have designed *Maneuver Templates*, common to all cooperative vehicles. Based on these, feasible maneuvers are given to the maneuver planner to facilitate planning in high-risk situations. If all vehicles know the same maneuver templates, complex maneuvers could be envisioned.

Lastly, Peng and Tomizuka [129] present a cooperation algorithm to enable the interaction of a human driver and an automated vehicle. They set human drivers' behavior as hard constraints in an optimization problem, making automated vehicles always yield to human drivers. They use persuasion, i.e., favoring cooperative driving strategies and concession, i.e., tuning the cost function weights. By this, their algorithm can take different human driver behaviors into account.

Since there is no cooperation in the sense of message exchanges involved in these solutions, it is only possible to assume or try to predict others' behavior. Communication-based approaches try to use the advantages of interactions in order to enable joint maneuvers involving all participants.

Prominent contributions: Most of the cooperative maneuver approaches published only consider automated vehicles. Therefore, Peng and Tomizuka's [129] approach for reconciling human drivers and automated vehicles could become a seminal paper for investigation of cooperation in mixed traffic situations.

Table IV compares all surveyed implicit and explicit approaches concerning crucial aspects. Firstly, the better vehicles can predict the future actions of others, the more confident they can choose their own subsequent actions. Here, (✓) means a partial predictability of others' reactions: known costs or objectives of their driving options allow for estimation of the most likely chosen maneuver, known roles provide at least a coarse understanding of the future behavior, and with the CLCS, the initiator knows that the maneuver partner will open a gap, even if it remains unclear how long this will take. Secondly, the approaches differ in how equally computational load to reach cooperation is distributed. For some, all participants draw their conclusions equally, while with others, one vehicle—most commonly the initiator—has a higher computational burden. Furthermore, the table lists the envisioned architecture options described in Section III. Since in implicit approaches the vehicles share data only about themselves, like intents or model parameters, computation and communication happen decentralized. Likewise, in explicit approaches most often the potential participants communicate as a group and request messages trigger the cooperative maneuvers.

B. Categorization of Implicit and Explicit Approaches

In this section, we propose several aspects along which to categorize cooperation protocols. Following these criteria, Table V summarizes the properties of the surveyed protocols. For this assessment, we took into consideration procedures as described in the various publications. We excluded approaches trying to achieve cooperation without communication because the provided grouping based on communication protocol properties does not apply to proposals relying only on an intelligent algorithm on each vehicle.

1) Exchanged Information: The first differentiation between protocols can be made based on what type of information participants exchange. Some protocols, especially implicit ones, work with the transmission of intended trajectories [55], [107]. Another approach is to exchange explicit intentions, for example, via a dedicated message or an abstract maneuver representation [56]. One may argue that trajectories are also explicit intentions, but we found it helpful to distinguish between the two. Trajectory descriptions are complex, requiring many Bytes for describing them and are accompanied by unsolved questions: "How many points and what time horizon shall be transmitted?", "What should be the time/space interval between two waypoints?", "Are those parameters static or dynamic?" to name a few.

In contrast, explicit intentions represent maneuvers differently: for example, a code representing a particular maneuver, plus specific parameters related to it. This approach necessitates a standardized dictionary of maneuver representations and possible parameters to ensure vehicles understand each other. Dedicated messages, e.g., a *Lane Change* message, also count as explicit intention. On the other hand, some proposals are based on the exchange of entirely different information,

TABLE V
CATEGORIZATION OF PROPOSED COOPERATIVE MANEUVER PROTOCOLS AND INVOLVED MESSAGES

	Enables Exchange of							
Protocol/ Message	Trajectories	Explicit Intentions	Others	Grouping	Applicability	Maneuver Representation	Transmission	Detection of Need for Maneuver
Implicit protocols								
Vehicle models [110]	✗	✗	✓	✗	General	None	Event-based	No negotiation
MCS (implicit) [55], [107], [118]	✓	✗	✗	✗	General	Waypoints	Periodic	Desired intersects planned trajectory
Motion options and costs [119]	✓	✗	✓	✗	General	Waypoints	Unknown	No negotiation
Maneuver primitives and costs [114], [120]	✗	✗	✓	✗	General	Parametrized maneuver primitives	Unknown	No negotiation
Explicit protocols								
CDAS [121]	Unknown	Unknown	✗	✗	General	Not specified	Event-based	Application logic
Merging [122]	✗	✓	✗	✗	Lane Merges	Merge behavior	Event-based	Road topology
CMP [116]	✗	✗	✓	Implicitly	General	Functions/roles	Event-based & periodic	Application logic
Space-time reservation [115], [124]	✗	✓	✓	✓ (for initiator)	General	Space-time box of road space	Event-based	Application logic
MCS (explicit) [125], [126]	✓	✗	✗	Implicitly	General	Trajectories	Event-based & periodic	Desired intersects planned trajectory
CVIP [117]	✓	✓	✓	Implicitly	General	Flexible	Event-based	Application logic
CLCS [56]	✗	✓	✗	✓	Lane Changes	Position & time	Event-based	Application logic
CLC [123]	✓	✗	✗	Implicitly	Lane Changes	Waypoints	Event-based	Motion planner

like model parameters [110], or they combine maneuver options with costs or other additional information [119].

2) Grouping: While all interactions have to happen between more than one vehicle by definition, there is a difference whether groups of vehicles are explicitly established or not. In the first case, a formal group is set up *before* a maneuver is discussed [102]. This step enables all vehicles to be aware of maneuver partners. The second possibility is group forming based on responses received from other vehicles, either via the ego vehicle selecting partners [56] or via adjusting the maneuver proposal [117]. In the third option, vehicles do not form groups at all, and every cooperation happens completely implicitly [107].

3) Applicability: Several studies have proposed application-specific protocols [56], [123]. These may allow efficient processing of information for their use case, but adjustments or new applications may require a separate, specialized protocol. General protocols [107], [115], [117] provide an alternative: they trade off efficiency with a larger set of use scenarios where participants can leverage the protocol with no or minor adjustments.

This applicability extends to the aspects enabled by certain protocols. While some can only be used for accepting the initial vehicles' maneuver [115], others can be used for determining all involved actors' maneuvers [117]. Some protocols also enable sharing information needed for a maneuver at hand [117], [121].

4) Representation: Protocols can describe the actual maneuvers to be performed in several ways. Application-specific procedures may represent maneuvers directly via the types of messages exchanged and the intrinsic knowledge about how participants should execute the use case. In Hobert *et al.* [56], a *Lane Change Request* stands strictly for a lane change, and all surrounding vehicles will understand this based on the protocol design. Likewise, the *Lane Change Response* implicitly indicates that the sender will open a gap.

Several options exist for deriving more complex maneuvers. Basic building blocks describe actions semantically. Another way to describe maneuvers is via trajectories, this means via time stamps and absolute coordinates or based on road geometry like via *Frenét* frames [135]. A third description is road space reservation, where the potentially moving road space the vehicles will take up at a certain point or period in time defines maneuvers [115]. While some protocols work with different representations [117], other researchers have developed theirs with a specific representation in mind [55], [118].

5) Transmission Mode: The periodic broadcast of beacons forms the basis of several protocols. CAMs/BSMs are exchanged by every V2X-enabled vehicle. Some studies propose extensions to them or new messages that would share perceived objects [136] or planned trajectories [107]. A different approach is the exchange of messages on-demand [56], [117].

The beacon-based transmission uses bandwidth roughly proportional to maneuver execution time, while demand-driven approaches may need additional procedures to identify potential maneuver partners [117].

C. Planning of Cooperative Maneuvers

There are several proposals on how to plan cooperative maneuvers. One advantage of implicit approaches is that the sharing of planned and desired trajectories enables all vehicles

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

to develop routes and trajectories that avoid collision while still allowing for cooperation. The individual motion planning units can plan routes and do not rely on confirmations by others. The cooperative motion planning is thus very similar to the "autarkic" one.

All other approaches need to find a way to determine cooperative maneuvers opportunities. Stemming from control theory, many procedures achieve this by optimizing different cost functions. Burger *et al.* [130] consider a cooperative cost function including terms for the individual vehicles and for interactions among them. How the individual cost terms should be combined is not stated. Kessler *et al.* [119] have proposed to share motion options and associated costs between vehicles. Vehicles subsequently minimize total cost, which is a weighted sum of individual cost terms. In such approaches, the vehicles potentially share information first, and then they derive a local optimal driving strategy. In the desired optimal case, this strategy—individually evaluated on each vehicle—allows for accident-free driving for all.

For other approaches, the initiating vehicles need to identify the need for a particular maneuver, e.g., a lane change. Once it identified this need, several possibilities exist depending on the protocol: with some approaches, the initiating vehicles propose this maneuver to surrounding vehicles, which then have to evaluate whether or not to cooperate, and if they choose to cooperate, then have to decide what to do [56]. Other methods place the burden of maneuver proposals on the initiator, who should first design a maneuver for all involved vehicles [117]. In such approaches, the remote vehicles can usually propose changes and adjust their part of the cooperative maneuver until it is acceptable.

Unfortunately, many studies from the field of motion planning for automated vehicles do not identify what kind of information would be most beneficial to get from other vehicles or to what extent maneuvers should be negotiated. For the most part, these studies do not consider the cooperative case but answer a motion planning related question from the point of view of one single vehicle. Graf *et al.* [131] only initiate overtakes if the algorithm guarantees collision-free, kinematically feasible trajectories at each planning step. Huang *et al.* [132] have considered control via hybrid automata for a cooperative platoon of vehicles. However, they do not focus on communication or the protocol for data exchange but instead model communication via a reliable and integral exchange of certain vehicle-related status information similar to BSMs. Based on these inputs, their controller generates control outputs used for platoon steering. Li *et al.* [133] have considered the problem of multiple vehicle lane changes and propose a centralized online optimization algorithm minimizing a combination of execution time and drastic steering angles. Their inputs are initial and target lanes, and they use look-up tables to evaluate which vehicles should change lanes. González *et al.* [42] and Paden *et al.* [41] provide extensive surveys on motion planning studies up to 2016. However, their overviews do not contain any planning algorithms for cooperative maneuvers.

As this section shows, there are a lot of different approaches towards cooperative maneuvers. This diversity is beneficial for finding reasonable solutions. However, in the end, players should agree on the same approach to ensure interoperability, at least within the big regions of the world.

V. STANDARDIZATION, ALLIANCES, PROJECTS

Along with the recent interest within the research community, the standardization of advanced cooperation mechanisms has also begun. Many industry alliances are related to the V2X concept, and an increasing number of governments at all levels (municipal, regional, national, and international) are funding projects on this topic.

A. *Current Standardization Efforts*

Different standardization efforts are going on across the globe. For a better overview, we split this section according to the most relevant regions, namely the US, China, Europe, and global associations. Where appropriate, we link the approaches from Section IV-A pursued in the relevant standards developing organizations (SDOs). For an overview on standardization regarding V2X in general, we refer the reader to [137]–[139].

1) United States: In the United States, most standardization related to advanced V2X use cases is going on in SAE International (SAE) [140]. More specifically, the V2X communications steering committee (SC) [141] deals with topics ranging from technological standardization [i.e., for DSRC and cellular V2X (C-V2X)] to topics like tolling via V2X. More specific to this paper, the *Advanced Applications* technical committee (TC) is currently working on the standard *J3186* [142]. It describes a protocol for cooperative maneuver negotiations with and without coordination by a central entity. While there is no clear timeline published yet, it can be expected that the TC will finish work on this standard project by 2022. As of May 2021, the standard improves the space-time reservation according to Heß *et al.* [124].

From the automated driving perspective, the SAE's Driver Assistance Systems SC [143] is publishing standards. Among them, J3216 [144] is defining terms related to cooperative driving. They divide cooperation into Class A (status sharing), Class B (intent sharing), Class C (agreement seeking), and Class D (prescriptive cooperation). While Class A entails *Day 1* cooperative awareness and *Day 2* cooperative perception, cooperative maneuvering as presented in this survey is part of Class C. In J3216, Class C is only foreseen for automated vehicles of Level 3 or higher as defined in J3016 [145].

2) China: In China, many standardization organizations exist, which are drafting standards on different hierarchical levels like group, industrial, or national standards. For V2X, mainly two nation-wide SDOs are of special importance. Under the Ministry of Industry and Information Technology (MIIT), the China Automotive Technology and Research Center Co, Ltd. (CATARC) [146] is concerned about all vehicle-related standards, while the China Communication Standards Association (CCSA) [147] is focused on communication-related standards. V2X as an interdisciplinary topic falls into the authority of both these organizations.

The MIIT strongly backs standardization for CCAM, as published in their *Construction Guidelines* for a standards system for intelligent and connected vehicles (ICVs) [148]. In 2017, a standard describing basic safety use cases called "Phase 1" and their minimum requirements was published [149]. Currently in 2021, both the CCSA and CATARC are working on "Phase 2" standards. These describe advanced use cases like cooperative lane change, cooperative sensing, or cooperative intersection crossing, without mentioning any specific protocols like the ones in Section IV-A. Chen *et al.* [150] also elaborate on the Chinese standards development, besides mentioning deployment projects and current developments in general.

3) Europe: For Europe, most standards regarding V2X, from network to application layer, are written by the European Telecommunications Standards Institute (ETSI) [151]. In ETSI especially, several current projects are related to advanced use cases. TS 103 561 [152] is based upon the work done by Lehmann *et al.* [55] with the first author being rapporteur for the work item. The goal is to describe a *Maneuver Coordination Service* involving the sharing of trajectories similar to Lehmann *et al.*'s approach. Recently, ETSI delegates also drafted TR 103 578 [153] regarding this topic. In parallel, TS 103 324 [154] and TR 103 562 [155] describe the *Cooperative Perception Service* based among others on Günther *et al.* [136].

4) Other Countries: Other countries have also identified the need for establishing a cooperative intelligent transport system (C-ITS). Nevertheless, their development is generally not as progressed as in the regions mentioned above. For example, in Korea the Ministry of Land, Infrastructure and Transport (MOLIT) is leading C-ITS activities, and ITS Korea [156] under it is responsible for standardization. Published in 2020, a news report [157] shows recent standardization and research projects, also mentioning cooperative driving. However, to the authors' best knowledge, there are no standards published yet on the topic.

5) Global: As the primary source of lower layer mobile communications standards, the 3GPP is currently developing their Release 17 specifications. 3GPP focuses mainly on the physical and MAC layers, therefore they will likely not introduce specifications for advanced V2X use cases or applications. However, requirements like in the "LTE support for V2X services" [109], derived from use cases, will influence work items trying to facilitate and improve advanced cooperation. Also, once specific approaches towards cooperative maneuvers are standardized, 3GPP may investigate how to add facilitators for these mechanisms in future releases.

In the International Organization for Standardization (ISO) [158], standardization on ITS is happening in ISO TC 204 [159], on a much more abstract level. In 2019, ISO17515-3 [160] was published specifying LTE-V as a possible access technology for ITSs.

Standards specifically for cooperative maneuvers are currently not aligned on a global scale. One reason may be that there is still little experience with cooperative maneuvers and which approach may be superior, if any. Therefore, each region standardizes a different approach just as they had specified different C-ITS message formats in the past. Since every region—the United States, China, and Europe—constitutes an extensive, isolated system with only a few vehicles driving from one to the other, the national standardization organizations do not pay much attention to interoperability on application or network layer. This differs from the globally harmonized development of mobile communications arising from increased traffic of people with mobile devices between the continents. Thus, interoperability seems to be of less concern for the moment, even though it should be a goal for the mid-term future.

As more research on cooperative maneuvers is published, this may also still affect standardization on that matter. Especially delivering objective criteria for a benchmark and comparisons of approaches seems to be necessary to choose optimal approaches for standards on cooperative maneuvers, see also Section VI-C5.

The normal mode of cooperation among SDOs is liaison statements, for example, to request a foreign standard document and incorporate aspects of it in their own standards. However, since the approaches pursued in the different SDOs differ substantially, the cooperation seems not as close for cooperative maneuvers as it is in other fields.

B. Involved Industry Alliances

Since V2X is an interdisciplinary subject, it was recognized early on that cross-industry alliances developing input for SDOs are valuable and necessary. The Car-to-Car Communication Consortium (C2C-CC) [161] was established as early as 2002. Mainly active in Europe, they develop specifications for the operation of V2X, harmonize ideas, e.g., from research projects, and propose work items for SDOs [162]. They are currently working on version 2.0 of their Basic System Profile [163] targeting *Day 2* services. As of May 2021, they did not release further details or documents on version 2.0.

Since motorcycles are often involved in fatal accidents, and yet their requirements are very different from four-wheelers, the Connected Motorcycle Consortium (CMC) [164] was set up in 2016. To promote safety for motorcycles, the CMC develops connectivity solutions for future C-ITSs. Because automated motorcycles are currently not under development, it is unclear whether the CMC will develop their own contributions for advanced cooperation. However, once SDOs and other organizations start to evaluate approaches on cooperation, the CMC may provide input for the applicability of the proposed solutions to the two-wheeler domain.

Also, in 2016, members from the automotive and telecommunication industries created the 5G Automotive Association (5GAA) [165], which now counts more than 130 members from both industry verticals. They published an industry road map of advanced use cases' mass-market deployment [3]. Another white paper describing such use cases including service-level requirements (SLRs) is under preparation [166].

Also related to mobile communications is the Next Generation Mobile Networks (NGMN), an alliance of mobile network operators and manufacturers founded in 2006 [167]. In 2018, they published a white paper on V2X [168]. No dedicated activities of NGMN towards cooperative maneuvers are known to the authors.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

All of the above organizations do not directly set standards, but they deliver input to SDOs. Besides those registered associations, Cusumano [1] mentions AD-related industry partnerships.

C. Government Supported Activities

Around the globe, governments are beginning to set up pilot projects with V2X deployments. Masini *et al.* [169] give an overview on government activities related to possible V2X mandates as of 2018. We will thus concentrate on newer activities and projects that involve cooperative maneuvering. In China especially, automation and connectivity are approached holistically, so the government will probably soon support cooperative maneuvering for automated vehicles as a next step. The National Development and Reform Commission (NDRC) published a "Strategy for Innovation and Development of Intelligent Vehicles" in February 2020 [170], and together with the MIIT's guidelines on vehicle management [171], these documents underline the expectation of the Chinese government to accelerate the development of V2X in China, especially in combination with AD. For Europe, Botte *et al.* [172] show that most governmental deployment activities are focused on *Day 1* and *Day 1.5* use cases.

Publicly funded projects related to V2X have existed for the last 2-3 decades. However, only a few newer ones involve advanced *Day 3/4* vehicular cooperation. We present them in chronological order of the funding period.

The European Autonet2030 project [173] (2013–2016) has investigated control and communication mechanisms for the use cases convoy driving, merging, and splitting as well as cooperative lane change [56].

The German IMAGinE project [174] (2016–2022) is concerned with assistance systems for cooperative driving. One outcome of this project was the implicit maneuver coordination based on trajectory sharing [107]. They considered six cooperative use cases on rural and highway roads.

While focusing on transitions between automated and non-automated driving states and infrastructure assistance, the TransAID project [175] (2017–2020) also proposed the introduction of the MCM for infrastructure advice to vehicles [118].

The AUTOPILOT project [176] (2017–2020) tries to embed automated vehicles into the Internet of things (IoT) based on the oneM2M platform [177], enabling sensor sharing with traffic lights, road sensors, and city cameras [178]. Their use cases include platooning and urban pedestrian detection.

The 5GCAR project [179] (2017–2020) designed, among others, a centralized lane merge traffic coordinator [112]. It takes unconnected and connected vehicles into account, but cooperation among vehicles is not the project's focus.

In the US, the Crash Avoidance Metrics Partnership (CAMP) [180] was formed in 1995 and has since conducted several research projects on vehicular safety, including V2X. One of their newest projects, cooperative automated driving systems (CADS) [181] (2018–2020), together with the Federal Highway Administration (FHWA), tries to augment CACC with information from the infrastructure. On the government side, the Federal Communcations Commission (FCC) issued a Notice of Proposed Rulemaking (NPRM) on the use of the 5.9 GHz band in 2020, that assigns formerly DSRC spectrum to commercial WiFi as well as C-V2X [182].

The 5G-CARMEN project [183] (2018–2021) tries to evaluate the benefits arising from 5G for AD. One of their four use cases is CLC, which they try to enable via a MEC server.

In Japan, the Strategic Innovation Promotion Program Automated Driving for Universal Services (SIP-adus) [184], funded by the cross-ministerial Council for Science, Technology and Innovation (CSTI), is developing automated driving. Its Phase 2 from 2019 to 2022 pilots AD in Tokyo for dynamic traffic information. They seemingly do not focus on communication and cooperation.

Those activities show that governments around the globe are interested in adopting V2X. How easily this will happen is still unclear since they need to resolve several practical issues. Partly, funded projects address these. Exemplarily, we name three such challenges. Firstly, it has to be legally allowed to use V2X in a country, i.e., sending on a specific frequency band for the purpose of a C-ITS. The mentioned FCC NPRM achieves this for LTE-V in the US. As long as no spectrum is assigned, the adoption of technology will be impossible. This is also true for advanced use cases which may need to use 5G-V2X, a technology for which currently no spectrum is assigned. Besides, the security credential management systems (SCMSs) envisioned for V2X are currently not in place in all relevant world regions. Most of the involved entities, e.g., root certification authorities, should be independent, potentially government-run bodies. However, necessary institutions and communication channels do not yet completely exist. A third challenge for the adoption of V2X is the customer. In Europe, sending out vehicle data is subject to the General Data Protection Regulation (GDPR) [185]. Therefore, in its current implemnetation, e.g., in the VW Golf VIII, drivers have to activate V2X in their cars and can deactivate it at any time. For V2X to become prevalent, citizen support and willingness is thus crucial.

VI. OPEN PROBLEMS AND FUTURE DIRECTIONS

Efforts are still necessary that will enable vehicular cooperation to become a reality. Some important ones are discussed below, chosen according to relevance as perceived by the authors and listed without prioritization. We concentrate on research aspects related to vehicular communication and omit purely AD-related ones like good motion planning algorithms.

A. Lessons Learned

Before presenting future directions, we summarize findings we gained from writing this literature review, adding our interpretation of the status quo.

Regarding architectures, a lot of research exists for traffic infrastructure to assist on large-scale traffic flow optimization, but not so much on smaller-scale decisions and facilitation, see Section VI-B3.

Most cooperative maneuver approaches mainly consider V2V communications. Studies present various proposals with different strengths and weaknesses. A next step could be to find synergies between approaches, thus enabling harmonizing standardization of different world regions.

Another missing aspect is the topic of safety, security, and privacy for cooperative maneuvers. For basic safety, this discussion is still not concluded, but for cooperative maneuvers it seems to just have started. When to switch certificates during or in between maneuvers, how to identify and avoid misbehavior, and how to prevent cooperative maneuvers from failing are just a few of the questions in this field. Häfner *et al.* [186] started looking into the latter question by suggesting mitigation mechanisms for several failure risks.

Lastly, even if studies have suggested many generally applicable protocols, the evaluation has been mostly restricted to specific scenarios: most prominently cooperative intersection crossing and lane change.

Next, we list the challenges that, in our opinion, need to be addressed regarding cooperative maneuvers.

B. Cooperation Architectures

Different architectures have been designed, but it is impossible to account for all aspects of future architectures at present.

1) Coevolution of Use Cases and Communication Technologies: Researchers should develop advanced communication technologies for future use scenarios. With the advancement of 5G-V2X, new possibilities will open up [187], [188]. It is clear that a technology choice made once cannot be suitable for all future applications. Next-generation communication technologies thus need to match expected use cases. If multiple RATs are in use, the second challenge will be enabling switching between technologies or mediating their coexistence. Whether a disjoint mapping of use cases to communication technologies (e.g., LTE-V2X for basic safety, 5G-V2X for maneuver coordination, 6G-V2X for even other use cases) is the best option has not yet been shown. If new technologies enable use cases already in the field, interoperability and compatibility will need to be ensured.

2) Mixed Traffic: Mixed traffic between connected and legacy, unconnected vehicles will be a challenge. Vehicles that cannot interact with connected vehicles can be considered obstacles. However, participation in the V2X ecosystem, e.g., via manufacturer backends or drivers' smartphones, would increase the penetration rate and benefit all traffic participants. Such integration may yield additional requirements for architectures.

Connected vehicles equipped with earlier versions of a cooperation protocol or low processing capabilities add another dimension of mixed traffic. Future studies should investigate potential ways of interaction with newer, more capable traffic participants.

3) Involvement of Infrastructure: Involving MEC servers may benefit vehicular cooperations. For cooperative perception, additional computing power and sensors can help recognize dangerous situations, but it is unclear how to involve them for cooperative maneuvers. RSUs may propose actions, but every vehicle itself should make the final decision on driven maneuvers. The challenge of handovers between edge nodes also needs to be considered. Potentially, computation and communication overheads outweigh the benefits of increased capabilities, but research has to investigate this.

4) Assessment of Architectures: Metrics to compare architectures for cooperative maneuvering are still unclear. Architectures suitable for distinct use scenarios but should be extensible to new use cases and communication technologies.

5) Size and Scalability: Most approaches for cooperative maneuvers were evaluated on simple scenarios using a few—typically 1 to 5—vehicles. Depending on the envisioned architectures for communication, computation, and decision-making, they may scale better or worse. When every vehicle decides on own actions, it may be easier to cooperate in large groups due to computational feasibility. On the other hand, message exchanges beween maneuver participants may render large groups intractable due to lossy channels. Häfner *et al.* [117] performed an initial quantitative analysis for the CVIP protocol on how the number of messages exchanged scales with the number of maneuver participants. However, a detailed analysis and comparison of how well different approaches and also different kinds of architectures scale and what advantages such scalability delivers is still an open research question. This question could be addressed in conjunction with general assessments on how practical given architectures are for real-world deployment, including large-scale, long-term testing.

C. Cooperative Maneuvers

Researchers should address the following open questions regarding cooperative maneuvers.

1) Cooperation Logic: In the IoV, it is essential to evaluate information's value before including them in the own driving strategy. For vehicle chains, Zhang designed a selection strategy on when to include information received over V2V into the decisions on acceleration or deceleration [189]. For cooperative maneuvers, researchers need to find approaches on how to assess proposals or requests from others. Currently, trajectory assessment is possible for the ego vehicle, but no method exists to evaluate whether an adjusted trajectory is worth driving to enable cooperation or not. In the best case, such assessment should take the overall benefit of cooperation into account, not only the advantages for the ego vehicle.

2) Application Logic: Decision strategies exist for initiating AD maneuvers like lane changes [190]–[192], partly involving information received via V2V [193]. With cooperative maneuvering, this is still lacking. For trajectory broadcasts, the HV needs to hope that RVs are willing to cooperate in the case of trajectory conflicts. Other approaches [115], [117] allow coordination among actors, but calculating proposals increases the HV's computational load. No study has yet described a strategy to ascertain whether a situation is worth the effort of finding a suitable complex maneuver to perform.

3) Choice of Maneuvers and Grouping: Vehicles may have to choose among maneuver options involving different sets of RVs. It is unclear how to prioritize them. Depending on the cooperation protocol, strategies of different complexity may have to be applied. In explicit approaches, the HV needs to assess before sending out a request. In implicit ones, it needs to consider the expected willingness of RVs when choosing which trajectory to send. A suboptimal trajectory may be more likely to be accommodated for and may thus be more successful than one minimizing the HV's costs. Here, either prediction on cooperation evaluation on the RVs or exchanges of model parameters analogous to [110] may be necessary.

It is not clear how to find *optimal* group sizes for certain maneuver types, situations, or cooperation protocols. Bigger groups are usually harder to maintain and synchronize, but the cooperation protocol and communication technologies used may influence feasible group sizes.

4) Combining Cooperative Maneuvering and Perception: Cooperative maneuvers could often benefit from additional information. We [117] combined maneuvering and information exchange, but several challenges still need to be addressed: How to assess the relevance of information is not clear, despite early approaches for *Day 1* like Adler *et al.* [194]. A method is needed to determine information from the infrastructure, RVs, or the HV that would benefit a situation. Additionally, studies should compare integrated approaches like in our work [117] to dedicated protocols for cooperative maneuvering and perception.

5) Evaluation of Cooperation Protocols: It is unclear which cooperation protocol is most suited for large-scale implementation. Some studies extend standardized messages, and others design new ones. Also, metrics to evaluate cooperative maneuver protocols are still missing. Studies emphasize communication metrics, employ traffic metrics, or show that their real-world setup is working. Some lack evaluation. Some studies include application requirements in an evaluation, e.g., Sepulcre and Gozalvez [195] for congestion control, or Jacob *et al.* [196] for communication profile selection, but not yet for cooperative maneuvers.

Such objective and generally applied benchmarks would also allow for comparing the computational resources needed for each cooperative maneuver protocol. Since these may differ, the protocol complexity potentially directly impacts hardware decisions and the most suitable (computation) architecture for cooperative maneuver deployments. Only a comparison of different approaches on similar hardware will show what requirements cooperative maneuvers pose to the onboard hardware and whether current products can already fulfill them.

Many open source datasets (cf. [48]) and benchmarks (e.g., CommonRoad [197]) exist for AD. As of 2021, none of these include cooperative maneuvers.

6) Implications of Cooperation for safety of the intended functionality: safety of the intended functionality (SOTIF) [198] is an important aspect for AD: ADASs have to ensure that actions will not lead to accidents or damage. Vehicles have to keep safety distances to objects to ensure that a stop or an evasive maneuver is possible even when surrounding vehicles behave unexpectedly. Some studies use formal methods for such an assessment [199]–[201]. Cooperative maneuvering may improve situation assessment, shortening necessary safety distances.

However, most systems evaluated from a SOTIF perspective are closed systems like a single vehicle. With cooperative maneuvering, a whole system of systems may have to be evaluated, rendering the assessment potentially more complex.

7) Security and Privacy: public key infrastructure (PKI)-based SCMSs including certificate revocation are foreseen for basic safety applications [202], [203]. Currently, it is unclear whether these mechanisms will suffice also for more advanced scenarios. Research exists on certificate change mechanisms [37], but cooperative maneuvers impose new requirements: can pseudonyms or certificates be exchanged during execution of a manuever? Cooperation also makes new sorts of attacks possible: depending on the protocol and the communication architecture used, attackers could send bogus requests to make cooperation possible.

Besides, the PKI serves the purpose of introducing anonymity [36]. However, for cooperative maneuvers the vehicles need a way to clearly identify and address potential maneuver partners. These are two conflicting interests that need to be resolved.

8) Trust: While systems such as PKI mentioned in the last section can improve authenticity and privacy, they do not provide measures to ensure the correctness of sent data. Such mechanisms would be needed to establish trust in other entities in the vehicular network.

Literature categorizes trust as entity-based, data-based, or combined trust [34]. Approaches to estimate or achieve trust exist for CAMs/BSMs and collective perception mechanisms, for example based on pair-wise comparison of provided information [204] or on fusion with local sensor data [205].

It is currently unclear whether such an approach is also sufficient for interactions requiring potentially different sorts of trust. Trust concepts for applications beyond *Day 2* not only need to verify that the information another vehicle sends is correct but also that it will perform the actions as committed to via the cooperative maneuver protocol. Promising ideas include "trust accounts" where vehicles could accumulate points for having performed as expected and would spend points for triggering cooperative maneuvers; or increasing liability, for example, via distributed ledgers and blockchain technologies [206]. However, this is not yet a satisfactory solution, as the problem of cheating once after a long period of good behavior cannot be mitigated. Such conduct is unacceptable in cooperative maneuvers, as it may have dire consequences.

As this section showed, many questions are still unanswered by research. For some, promising ideas exist, while others seem relatively untouched, yet.

VII. CONCLUSION

In this survey paper, we summarized current research related to advanced vehicular cooperation. We have shown that several different approaches towards cooperative maneuvers for automated vehicles exist. It is not yet clear which of the approaches built on different architectures will be most beneficial. Similar to basic safety V2X, avoiding regionally different solutions requires globally aligned development and standardization. However, to optimally decide on realizations, a significant amount of additional research is still needed. We have pointed out several research challenges to encourage the community to rivet their attention to required advancements. With joint efforts, advanced cooperation among automated vehicles can and will soon become a reality.

APPENDIX

List of acronyms:

3GPP	Third Generation Partnership Project
5G	Fifth Generation Cellular Communication
5GAA	5G Automotive Association
AD	automated driving
ADAS	advanced driver assistance system
BSM	Basic Safety Message
C2C-CC	Car-to-Car Communication Consortium
CACC	cooperative adaptive cruise control
CADS	cooperative automated driving systems
CAM	Cooperative Awareness Message
CAMP	Crash Avoidance Metrics Partnership
CAV	connected and automated vehicles
CATARC	China Automotive Technology and Research Center Co, Ltd.
CCAM	cooperative, connected, and automated mobility
CCSA	China Communication Standards Association
CDAS	cooperative driver assistance system
C-ITS	cooperative intelligent transport system
CLC	cooperative lane change
CLCS	cooperative lane change service
CMC	Connected Motorcycle Consortium
CMP	collaborative maneuver protocol
CQM	Cooperative Request Message
CRM	Cooperative Response Message
CSTI	Council for Science, Technology and Innovation
C-V2X	cellular V2X
CVIP	Complex Vehicular Interactions Protocol
D2D	device-to-device
DSRC	dedicated short-range communication
EC	European Commission
ETSI	European Telecommunications Standards Institute
FCC	Federal Communcations Commission
FHWA	Federal Highway Administration
GDPR	General Data Protection Regulation
HV	host vehicle
ICN	information-centric network
ICV	intelligent and connected vehicle
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of things
IoV	Internet of vehicles
ISO	International Organization for Standardization
ITS	intelligent transport system
LTE	Long-Term Evolution
LTE-V	vehicular LTE
MAC	medium access control
MCM	Maneuver Coordination Message
MCS	Maneuver Coordination Service
MEC	multi-access edge computing
MIIT	Ministry of Industry and Information Technology
MFM	Maneuver Feedback Message
MOLIT	Ministry of Land, Infrastructure and Transport
MPC	model predictive control
MSM	Maneuver Status Message
NDRC	National Development and Reform Commission
NGMN	Next Generation Mobile Networks
NPRM	Notice of Proposed Rulemaking
PDR	packet delivery ratio
PER	packet error rate
PKI	public key infrastructure
RAT	radio access technology
RSU	road side unit
RV	remote vehicle
SAE	SAE International
SC	steering committee
SCMS	security credential management system
SDO	standards developing organization
SLR	service-level requirement
SOTIF	safety of the intended functionality
TC	technical committee
V2I	vehicle-to-infrastructure
V2N	vehicle-to-network
V2P	vehicle-to-pedestrian
V2V	vehicle-to-vehicle
V2X	vehicle-to-everything
VANET	vehicular ad-hoc network

REFERENCES

[1] M. A. Cusumano, "Self-driving vehicle technology: Progress and promises," *Commun. ACM*, vol. 63, no. 10, pp. 20–22, Oct. 2020. doi: 10.1145/3417074

[2] J. Wang, J. Liu, and N. Kato, "Networking and communications in autonomous driving: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1243–1274, 2nd Quart. 2019. doi: 10.1109/COMST.2018.2888904

[3] "A visionary roadmap for advanced driving use cases, connectivity technologies, and radio spectrum needs," 5G Automotive Association, White Paper, Sep. 2020. [Online]. Available: https://bit.ly/32dUmBD

[4] M. Gerla, E. K. Lee, G. Pau, and U. Lee, "Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds," in *Proc. IEEE World Forum Internet Things (WF-IoT)*, Mar. 2014, pp. 241–246. doi: 10.1109/WF-IoT.2014.6803166

[5] J. Cheng, J. Cheng, M. Zhou, F. Liu, S. Gao, and C. Liu, "Routing in Internet of vehicles: A review," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2339–2352, May 2015. doi: 10.1109/TITS.2015.2423667

[6] H. Zhou, W. Xu, J. Chen, and W. Wang, "Evolutionary V2X technologies toward the Internet of vehicles: Challenges and opportunities," *Proc. IEEE*, vol. 108, no. 2, pp. 308–323, Feb. 2020. doi: 10.1109/JPROC.2019.2961937

[7] L. Li, D. Wen, and D. Yao, "A survey of traffic control with vehicular communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 425–432, Feb. 2014. doi: 10.1109/TITS.2013.2277737

[8] J.-C. Köstring, T. Möller, S. Middleton, A. Tschiesner, and A. Padhi, "The new realities of premium mobility," McKinsey Center for Future Mobility, Rep., Nov. 2019. [Online]. Available: https://mck.co/2EnSxbL

[9] Business Wire. (2016, Nov.) Vehicles getting older. [Online]. Available: www.businesswire.com/news/home/20161122005119/en/

[10] M. Alsabaan, W. Alasmary, A. Albasir, and K. Naik, "Vehicular networks for a greener environment: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1372–1388, 3rd Quart. 2013. doi: 10.1109/SURV.2012.101912.00184

[11] S. Djahel, R. Doolan, G.-M. Muntean, and J. Murphy, "A communications-oriented perspective on traffic management systems for smart cities: Challenges and innovative approaches," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 125–151, 1st Quart. 2015. doi: 10.1109/COMST.2014.2339817

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/COMST.2021.3138275, IEEE Communications Surveys & Tutorials

[12] N. Wang, X. Wang, P. Palacharla, and T. Ikeuchi, “Cooperative autonomous driving for traffic congestion avoidance through vehicle-to-vehicle communications,” in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2018, pp. 327–330. doi: 10.1109/VNC.2017.8275620

[13] H. Rakha and R. K. Kamalanathsharma, “Eco-driving at signalized intersections using V2I communication,” in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2011, pp. 341–346. doi: 10.1109/ITSC.2011.6083084

[14] S. Darbha, S. Konduri, and P. R. Pagilla, “Benefits of V2V communication for autonomous and connected vehicles,” *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 5, pp. 1954–1963, Sep. 2019. doi: 10.1109/TITS.2018.2859765

[15] S. Kuk, Y. Park, and H. Kim, “Pseudo-broadcast: An alternative mode of vehicular communication for platooning,” *IEEE Commun. Mag.*, vol. 57, no. 6, pp. 56–61, Jun. 2019. doi: 10.1109/MCOM.2019.1800941

[16] S. Mariani, G. Cabri, and F. Zambonelli, “Coordination of autonomous vehicles: Taxonomy and survey,” *ACM Comput. Surveys*, vol. 54, no. 1, pp. 19:1–19:33, Feb. 2021. doi: 10.1145/3431231

[17] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, “A survey on platoon-based vehicular cyber-physical systems,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 263–284, 1st Quart. 2016. doi: 10.1109/COMST.2015.2410831

[18] J. Axelsson, “Safety in vehicle platooning: A systematic literature review,” *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 5, pp. 1033–1045, May 2017. doi: 10.1109/TITS.2016.2598873

[19] *Road Vehicles – Functional Safety*, ISO Std. 26 262, Dec. 2018. [Online]. Available: https://www.iso.org/standard/68383.html

[20] L. Chen and C. Englund, “Cooperative intersection management: A survey,” *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 570–586, Feb. 2016. doi: 10.1109/TITS.2015.2471812

[21] J. Rios-Torres and A. A. Malikopoulos, “A survey on the coordination of connected and automated vehicles at intersections and merging at highway on-ramps,” *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 5, pp. 1066–1077, May 2017. doi: 10.1109/TITS.2016.2600504

[22] G. Naik, B. Choudhury, and J. M. Park, “IEEE 802.11bd & 5G NR V2X: Evolution of radio access technologies for V2X communications,” *IEEE Access*, vol. 7, pp. 70 169–70 184, May 2019. doi: 10.1109/ACCESS.2019.2919489

[23] W. Anwar, N. Franchi, and G. Fettweis, “Physical layer evaluation of v2x communications technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p,” in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Sep. 2019, pp. 406:1–406:7. doi: 10.1109/VTC-Fall.2019.8891313

[24] A. Mansouri, V. Martinez, and J. Härri, “A first investigation of congestion control for LTE-V2X mode 4,” in *Proc. Annu. Conf. Wireless On-Demand Netw. Syst. Services (WONS)*, Jan. 2019, pp. 56–63. doi: 10.23919/WONS.2019.8795500

[25] A. Möller and T. Kürner, “LTE link level performance evaluation using stochastic channel models for V2X communication,” in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2016, pp. 25–31. doi: 10.1109/VNC.2015.7385542

[26] G. Cecchini, A. Bazzi, B. M. Masini, and A. Zanella, “Performance comparison between IEEE 802.11p and LTE-V2V in-coverage and out-of-coverage for cooperative awareness,” in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2017, pp. 109–114. doi: 10.1109/VNC.2017.8275637

[27] A. Bazzi, G. Cecchini, M. Menarini, B. M. Masini, and A. Zanella, “Survey and perspectives of vehicular Wi-Fi versus sidelink Cellular-V2X in the 5G era,” *Future Internet*, vol. 11, no. 6, pp. 122:1–122:20, Jun. 2019. doi: 10.3390/fi11060122

[28] L. G. Baltar, M. Mueck, and D. Sabella, “Heterogeneous vehicular communications – multi-standard solutions to enable interoperability,” in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Oct. 2018, pp. 8:1–8:6. doi: 10.1109/CSCN.2018.8581726

[29] J. Wang, Y. Shao, Y. Ge, and R. Yu, “A survey of vehicle to everything (V2X) testing,” *Sensors*, vol. 19, no. 2, pp. 334:1–334:20, Jan. 2019. doi: 10.3390/s19020334

[30] Z. MacHardy, A. Khan, K. Obana, and S. Iwashina, “V2X access technologies: Regulation, research, and remaining challenges,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1858–1877, 3rd Quart. 2018. doi: 10.1109/COMST.2018.2808444

[31] M. Hadded, P. Muhlethaler, A. Laouiti, R. Zagrouba, and L. A. Saidane, “TDMA-based MAC protocols for vehicular ad hoc networks: A survey, qualitative analysis, and open research issues,” *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2461–2492, 4th Quart. 2015. doi: 10.1109/COMST.2015.2440374

[32] M. H. Castaneda Garcia, A. Molina-Galan, M. Boban, J. Gozalvez, B. Coll-Perales, T. Sahin, and A. Kousaridas, “A tutorial on 5G NR V2X communications,” *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1972–2026, 3rd Quart. 2021. doi: 10.1109/COMST.2021.3057017

[33] A. Awang, K. Husain, N. Kamel, and S. Aissa, “Routing in vehicular ad-hoc networks: A survey on single- and cross-layer design techniques, and perspectives,” *IEEE Access*, vol. 5, pp. 9497–9517, Apr. 2017. doi: 10.1109/ACCESS.2017.2692240

[34] X. Wang, Z. Ning, M. C. Zhou, X. Hu, L. Wang, Y. Zhang, F. R. Yu, and B. Hu, “Privacy-preserving content dissemination for vehicular social networks: Challenges and solutions,” *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1314–1345, 2nd Quart. 2019. doi: 10.1109/COMST.2018.2882064

[35] R. W. Van Der Heijden, S. Dietzel, T. Leinmüller, and F. Kargl, “Survey on misbehavior detection in cooperative intelligent transportation systems,” *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 779–811, 1st Quart. 2019. doi: 10.1109/COMST.2018.2873088

[36] J. Petit, F. Schaub, M. Feiri, and F. Kargl, “Pseudonym schemes in vehicular networks: A survey,” *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 228–255, 1st Quart. 2015. doi: 10.1109/COMST.2014.2345420

[37] A. Boualouache, S. M. Senouci, and S. Moussaoui, “A survey on pseudonym changing strategies for vehicular ad-hoc networks,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 770–790, 1st Quart. 2018. doi: 10.1109/COMST.2017.2771522

[38] Z. Lu, G. Qu, and Z. Liu, “A survey on recent advances in vehicular network security, trust, and privacy,” *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 2, pp. 760–776, Feb. 2019. doi: 10.1109/TITS.2018.2818888

[39] A. Masood, D. S. Lakew, and S. Cho, “Security and privacy challenges in connected vehicular cloud computing,” *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2725–2764, 4th Quart. 2020. doi: 10.1109/COMST.2020.3012961

[40] D. Bevly, X. Cao, M. Gordon, G. Ozbilgin, D. Kari, B. Nelson, J. Woodruff, M. Barth, C. Murray, A. Kurt, K. Redmill, and U. Ozguner, “Lane change and merge maneuvers for connected and automated vehicles: A survey,” *IEEE Trans. Intell. Veh.*, vol. 1, no. 1, pp. 105–120, Jul. 2016. doi: 10.1109/tiv.2015.2503342

[41] B. Paden, M. Cap, S. Z. Yong, D. Yershov, and E. Frazzoli, “A survey of motion planning and control techniques for self-driving urban vehicles,” *IEEE Trans. Intell. Veh.*, vol. 1, no. 1, pp. 33–55, Mar. 2016. doi: 10.1109/tiv.2016.2578706

[42] D. González, J. Pérez, V. Milanés, and F. Nashashibi, “A review of motion planning techniques for automated vehicles,” *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 4, pp. 1135–1145, Apr. 2016. doi: 10.1109/TITS.2015.2498841

[43] W. Schwarting, J. Alonso-Mora, and D. Rus, “Planning and decision-making for autonomous vehicles,” *Annu. Rev. Control Robot. Auton. Syst.*, vol. 1, no. 1, pp. 187–210, May 2018. doi: 10.1146/annurev-control-060117-105157

[44] S. Aradi, “Survey of deep reinforcement learning for motion planning of autonomous vehicles,” *IEEE Trans. Intell. Transp. Syst.*, pp. 1–20, 2020. doi: 10.1109/tits.2020.3024655 Accepted for publication.

[45] G. Bresson, Z. Alsayed, L. Yu, and S. Glaser, “Simultaneous localization and mapping: A survey of current trends in autonomous driving,” *IEEE Trans. Intell. Veh.*, vol. 2, no. 3, pp. 194–220, Sep. 2017. doi: 10.1109/TIV.2017.2749181

[46] S. Gyawali, S. Xu, Y. Qian, and R. Q. Hu, “Challenges and solutions for cellular based V2X communications,” *IEEE Commun. Surveys Tuts.*, vol. 23, no. 1, pp. 222–255, 1st Quart. 2021. doi: 10.1109/comst.2020.3029723

[47] R. Hussain and S. Zeadally, “Autonomous cars: Research results, issues, and future challenges,” *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1275–1313, 2nd Quart. 2019. doi: 10.1109/COMST.2018.2869360

[48] E. Yurtsever, J. Lambert, A. Carballo, and K. Takeda, “A survey of autonomous driving: Common practices and emerging technologies,” *IEEE Access*, vol. 8, pp. 58 443–58 469, Mar. 2020. doi: 10.1109/ACCESS.2020.2983149

[49] *Dedicated Short Range Communications (DSRC) Message Set Dictionary*, SAE Std. J2735, Dec. 2006.

[50] *IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, IEEE Std. 802.11p-2010, Jul. 2010. doi: 10.1109/IEEESTD.2010.5514475

[51] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*, ETSI TS 102 637-2, Rev. 1.1.1, Apr. 2010.

[52] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall Description; Stage 2*, 3GPP TS 36.300, Rev. 12.0.0, Jan. 2014. [Online]. Available: www.3gpp.org/ftp/Specs/archive/36_series/36.300/36300-c00.zip

[53] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall Description; Stage 2*, 3GPP TS 36.300, Rev. 14.0.0, Sep. 2016. [Online]. Available: www.3gpp.org/ftp/Specs/archive/36_series/36.300/36300-e00.zip

[54] *On-Board System Requirements for V2V Safety Communications*, SAE Std. J2945, Mar. 2016.

[55] B. Lehmann, H.-J. Günther, and L. Wolf, "A generic approach towards maneuver coordination for automated vehicles," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 3333–3339. doi: 10.1109/ITSC.2018.8569442

[56] L. Hobert, A. Festag, I. Llatser, L. Altomare, F. Visintainer, and A. Kovacs, "Enhancements of V2X communication in support of cooperative autonomous driving," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 64–70, Dec. 2015. doi: 10.1109/MCOM.2015.7355568

[57] L. Briesemeister, L. Schäfers, and G. Hommel, "Disseminating messages among highly mobile hosts based on inter-vehicle communication," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Oct. 2000, pp. 522–527. doi: 10.1109/ivs.2000.898398

[58] B. Mourllion, A. Lambert, D. Gruyer, and D. Aubert, "Collaborative perception for collision avoidance," in *Proc. IEEE Int. Conf. Netw., Sens. Control (ICNSC)*, Mar. 2004, pp. 880–885. doi: 10.1109/icnsc.2004.1297063

[59] Y. Toor, P. Mühlethaler, A. Laouiti, and A. De La Fortelle, "Vehicle ad hoc networks: Applications and related technical issues," *IEEE Commun. Surveys Tuts.*, vol. 10, no. 3, pp. 74–88, 3rd Quart. 2008. doi: 10.1109/COMST.2008.4625806

[60] M. L. Sichitiu and M. Kihl, "Inter-vehicle communication systems: A survey," *IEEE Commun. Surveys Tuts.*, vol. 10, no. 2, pp. 88–105, 2nd Quart. 2008. doi: 10.1109/COMST.2008.4564481

[61] H. Hartenstein and K. P. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *IEEE Commun. Mag.*, vol. 46, no. 6, pp. 164–171, Jun. 2008. doi: 10.1007/978-3-642-36169-2

[62] S. Al-Sultan, M. M. Al-Doori, A. H. Al-Bayatti, and H. Zedan, "A comprehensive survey on vehicular ad hoc network," *J. Netw. Comput. Appl.*, vol. 37, pp. 380–392, Jan. 2014. doi: 10.1016/j.jnca.2013.02.036

[63] R. Coppola and M. Morisio, "Connected car: Technologies, issues future trends," *ACM Comput. Surveys*, vol. 49, no. 3, pp. 46:1–46:36, Oct. 2016. doi: 10.1145/2971482

[64] T. L. Willke, P. Tientrakool, and N. F. Maxemchuk, "A survey of inter-vehicle communication protocols and their applications," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 2, pp. 3–20, 2nd Quart. 2009. doi: 10.1109/SURV.2009.090202

[65] O. Sawade and I. Radusch, "Survey and classification of cooperative automated driver assistance systems," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Sep. 2015, pp. 389:1–389:5. doi: 10.1109/VTC-Fall.2015.7391161

[66] J. Chennikara-Varghese, W. Chen, O. Altintas, and S. Cai, "Survey of routing protocols for inter-vehicle communications," in *Proc. Annu. Int. Conf. Mobile Ubiquitous Syst: Netw. Services*, Jul. 2006, pp. 51:1–51:5. doi: 10.1109/MOBIQ.2006.340432

[67] S. Panichpapiboon and W. Pattara-atikom, "A review of information dissemination protocols for vehicular ad hoc networks," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 3, pp. 784–798, 3rd Quart. 2012. doi: 10.1109/SURV.2011.070711.00131

[68] S. M. Bilal, C. J. Bernardos, and C. Guerrero, "Position-based routing in vehicular networks: A survey," *J. Netw. Comput. Appl.*, vol. 36, no. 2, pp. 685–697, Mar. 2013. doi: 10.1016/j.jnca.2012.12.023

[69] E. Ahmed and H. Gharavi, "Cooperative vehicular networking: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 3, pp. 996–1014, Feb. 2018. doi: 10.1109/TITS.2018.2795381

[70] F. Dressler, F. Klingler, C. Sommer, and R. Cohen, "Not all VANET broadcasts are the same: Context-aware class based broadcast," *IEEE/ACM Trans. Netw.*, vol. 26, no. 1, pp. 17–30, Oct. 2018. doi: 10.1109/TNET.2017.2763185

[71] R. S. Bali, N. Kumar, and J. J. Rodrigues, "Clustering in vehicular ad hoc networks: Taxonomy, challenges and solutions," *Veh. Commun.*, vol. 1, no. 3, pp. 134–152, Jul. 2014. doi: 10.1016/j.vehcom.2014.05.004

[72] C. Cooper, D. Franklin, M. Ros, F. Safaei, and M. Abolhasan, "A comparative survey of VANET clustering techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 657–681, 1st Quart. 2017. doi: 10.1109/COMST.2016.2611524

[73] D. Grewe, M. Wagner, and H. Frey, "A domain-specific comparison of information-centric networking architectures for connected vehicles," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2372–2388, 3rd Quart. 2018. doi: 10.1109/COMST.2018.2817653

[74] H. Khelifi, S. Luo, B. Nour, H. Moungla, Y. Faheem, R. Hussain, and A. Ksentini, "Named data networking in vehicular ad hoc networks: State-of-the-art and challenges," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 320–351, 1st Quart. 2019. doi: 10.1109/COMST.2019.2894816

[75] D. Reichardt, M. Miglietta, L. Moretti, P. Morsink, and W. Schulz, "CarTALK 2000: Safe and comfortable driving based upon inter-vehicle-communication," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2002, pp. 545–550. doi: 10.1109/ivs.2002.1188007

[76] *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall Description; Stage 2*, 3GPP TS 36.300, Rev. 16.0.0, Dec. 2019. [Online]. Available: www.3gpp.org/ftp/Specs/archive/36_series/36.300/36300-g00.zip

[77] S. Ucar, S. C. Ergen, and O. Ozkasap, "Multihop-cluster-based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2621–2636, Apr. 2016. doi: 10.1109/TVT.2015.2421277

[78] *Study on LTE Support for Vehicle to Everything (V2X) Services*, 3GPP TR 22.885, Rev. 14.0.0, Dec. 2015. [Online]. Available: www.3gpp.org/ftp/Specs/archive/22_series/22.885/22885-e00.zip

[79] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro, "LTE for vehicular networking: A survey," *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 148–157, May 2013. doi: 10.1109/MCOM.2013.6515060

[80] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou, "Heterogeneous vehicular networking: A survey on architecture, challenges, and solutions," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2377–2396, 4th Quart. 2015. doi: 10.1109/COMST.2015.2440103

[81] K. Abboud, H. A. Omar, and W. Zhuang, "Interworking of DSRC and cellular network technologies for V2X communications: A survey," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 9457–9470, Jul. 2016. doi: 10.1109/TVT.2016.2591558

[82] A. Zekri and W. Jia, "Heterogeneous vehicular communications: A comprehensive study," *Ad Hoc Netw.*, vol. 75, pp. 52–79, Jun. 2018. doi: 10.1016/j.adhoc.2018.03.010

[83] N. Hehenkamp, C. Facchi, and S. Neumeier, "How to achieve traffic safety with LTE and edge computing," in *Proc. Future Inf. Commun. Conf. (FICC)*, Mar. 2019, pp. 164–176. doi: 10.1007/978-3-030-12388-8_12

[84] T. Taleb, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella, "On multi-access edge computing: A survey of the emerging 5G network edge cloud architecture and orchestration," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1657–1681, 3rd Quart. 2017. doi: 10.1109/COMST.2017.2705720

[85] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: The communication perspective," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2322–2358, 4th Quart. 2017. doi: 10.1109/COMST.2017.2745201

[86] S. W. Kim, B. Qin, Z. J. Chong, X. Shen, W. Liu, M. H. Ang, E. Frazzoli, and D. Rus, "Multivehicle cooperative driving using cooperative perception: Design and experimental validation," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 663–680, Jul. 2015. doi: 10.1109/TITS.2014.2337316

[87] J. Shi, W. Wang, X. Wang, H. Sun, X. Lan, J. Xin, and N. Zheng, "Leveraging spatio-temporal evidence and independent vision channel to improve multi-sensor fusion for vehicle environmental perception," in *Proc. IEEE Intell. Veh. Symp. (IV)*, 2018, pp. 591–596. doi: 10.1109/IVS.2018.8500665

[88] F. A. Schiegg, N. Brahmi, and I. Llatser, "Analytical performance evaluation of the collective perception service in C-V2X mode 4 networks," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2019, pp. 181–188. doi: 10.1109/ITSC.2019.8917214

[89] Q. Chen, S. Tang, Q. Yang, and S. Fu, "Cooper: Cooperative perception for connected autonomous vehicles based on 3D point clouds," in *Proc. IEEE Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Jul. 2019, pp. 514–524. doi: 10.1109/ICDCS.2019.00058

[90] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, "Analysis of message generation rules for collective perception in connected and automated

driving," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2019, pp. 134–139. doi: 10.1109/IVS.2019.8813806

[91] F. A. Schiegg, D. Bischoff, J. R. Krost, and I. Llatser, "Analytical performance evaluation of the collective perception service in IEEE 802.11p networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, May 2020, pp. 1–6. doi: 10.1109/WCNC45663.2020.9120490

[92] J. Vantomme, "Towards cooperated, connected and automated driving in Europe," presented at the ITU Forum 5G Gigabit Soc., Athens, Greece, Oct. 2018. [Online]. Available: https://bit.ly/2COJjVS

[93] J. E. Doran, S. Franklin, N. R. Jennings, and T. J. Norman, "On cooperation in multi-agent systems," *Knowl. Eng. Rev.*, vol. 12, no. 3, pp. 309–314, 1997. [Online]. Available: https://bit.ly/3hKT1rk

[94] C. Burger, P. F. Orzechowski, O. S. Tas, and C. Stiller, "Rating cooperative driving: A scheme for behavior assessment," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2018, pp. 1–6. doi: 10.1109/ITSC.2017.8317794

[95] Y. Meng, L. Li, F.-Y. Wang, K. Li, and Z. Li, "Analysis of cooperative driving strategies for nonsignalized intersections," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 2900–2911, Dec. 2018. doi: 10.1109/TVT.2017.2780269

[96] S. Kato, M. Hiltunen, K. Joshi, and R. Schlichting, "Enabling vehicular safety applications over LTE networks," in *Proc. IEEE Int. Conf. Connected Veh. Expo (ICCVE)*, Dec. 2013, pp. 747–752. doi: 10.1109/ICCVE.2013.6799889

[97] H. Zhang, X. Chu, W. Guo, and S. Wang, "Coexistence of Wi-Fi and heterogeneous small cell networks sharing unlicensed spectrum," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 158–164, Mar. 2015. doi: 10.1109/MCOM.2015.7060498

[98] T. Taleb and A. Benslimane, "Design guidelines for a network architecture integrating VANET with 3G & beyond networks," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2010, pp. 1–5. doi: 10.1109/GLOCOM.2010.5684061

[99] N. Dreyer, A. Möller, Z. H. Mir, F. Filali, and T. Kürner, "A data traffic steering algorithm for IEEE 802.11p/LTE hybrid vehicular networks," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Sep. 2016, pp. 1–6. doi: 10.1109/VTCFall.2016.7880850

[100] F. Abbas, P. Fan, and Z. Khan, "A novel low-latency V2V resource allocation scheme based on cellular V2X communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 6, pp. 2185–2197, Oct. 2019. doi: 10.1109/TITS.2018.2865173

[101] H. King, K. Nolan, and M. Kelly, "Interoperability between DSRC and LTE for VANETs," in *Proc. IEEE Int. Symp. Ind. Embedded Syst. (SIES)*, Jun. 2018, pp. 1–8. doi: 10.1109/SIES.2018.8442086

[102] C. Frese, J. Beyerer, and P. Zimmer, "Cooperation of cars and formation of cooperative groups," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2007, pp. 227–232. doi: 10.1109/ivs.2007.4290119

[103] S. Zeadally, M. A. Javed, and E. B. Hamida, "Vehicular communications for ITS: Standardization and challenges," *IEEE Commun. Standards Mag.*, vol. 4, no. 1, pp. 11–17, Mar. 2020. doi: 10.1109/MCOM-STD.001.1900044

[104] X. Qian, A. De La Fortelle, and F. Moutarde, "A hierarchical model predictive control framework for on-road formation control of autonomous vehicles," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2016, pp. 376–381. doi: 10.1109/IVS.2016.7535413

[105] S. Tsugawa, S. Kato, T. Matsui, H. Naganawa, and H. Fujii, "An architecture for cooperative driving of automated vehicles," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2000, pp. 422–427. doi: 10.1109/ITSC.2000.881102

[106] J. Lee, H. Ko, and S. Pack, "Trajectory-aware edge node clustering in vehicular edge clouds," in *Proc. IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2019, pp. 1–4. doi: 10.1109/CCNC.2019.8651870

[107] I. Llatser, T. Michalke, M. Dolgov, F. Wildschütte, and H. Fuchs, "Cooperative automated driving use cases for 5G V2X communication," in *Proc. IEEE 5G World Forum (5GWF)*, Sep. 2019, pp. 120–125. doi: 10.1109/5GWF.2019.8911628

[108] (2020, Sep.) IEEE P802.11 Task Group bd: Enhancements for Next Generation V2X project website. [Online]. Available: www.ieee802.org/11/Reports/tgbd_update.htm

[109] *Technical Specification Group Services and System Aspects; Study on Enhancement of 3GPP Support for 5G V2X Services (Release 16)*, 3GPP TR 22.886, Rev. 16.2.0, Dec. 2018. [Online]. Available: www.3gpp.org/ftp//Specs/archive/22_series/22.886/22886-g20.zip

[110] E. Moradi-Pari, H. N. Mahjoub, H. Kazemi, Y. P. Fallah, and A. Tahmasbi-Sarvestani, "Utilizing model-based communication and control for cooperative automated vehicle applications," *IEEE Trans. Intell. Veh.*, vol. 2, no. 1, pp. 38–51, Mar. 2017. doi: 10.1109/tiv.2017.2708605

[111] J. A. Michon, "A critical view of driver behavior models: What do we know, what should we do?" in *Human Behavior and Traffic Safety*, L. Evans and R. C. Schwing, Eds. Boston, MA: Springer, 1985, pp. 485–520. doi: 10.1007/978-1-4613-2173-6_19

[112] L. Sequeira, A. Szefer, J. Slome, and T. Mahmoodi, "A lane merge coordination model for a V2X scenario," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2019, pp. 198–203. doi: 10.1109/EuCNC.2019.8801987

[113] S. Manzinger, M. Leibold, and M. Althoff, "Driving strategy selection for cooperative vehicles using maneuver templates," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2017, pp. 647–654. doi: 10.1109/IVS.2017.7995791

[114] M. Düring and P. Pascheka, "Cooperative decentralized decision making for conflict resolution among autonomous agents," in *Proc. IEEE Int. Symp. Innov. Intell. Syst. Appl. (INISTA)*, Jun. 2014, pp. 154–161. doi: 10.1109/INISTA.2014.6873612

[115] D. Heß, R. Lattarulo, J. Pérez, T. Hesse, and F. Köster, "Negotiation of cooperative maneuvers for automated vehicles: Experimental results," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2019, pp. 1545–1551. doi: 10.1109/ITSC.2019.8917464

[116] O. Sawade, M. Schulze, and I. Radusch, "Robust communication for cooperative driving maneuvers," *IEEE Intell. Transp. Syst. Mag.*, vol. 10, no. 3, pp. 159–169, Jun. 2018. doi: 10.1109/MITS.2018.2842241

[117] B. Häfner, J. Jiru, K. Roscher, J. Ott, G. A. Schmitt, and Y. Sevilmis, "CVIP: A protocol for complex interactions among connected vehicles," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Oct. 2020, pp. 510–515. doi: 10.1109/IV47402.2020.9304556

[118] A. Correa, R. Alms, J. Gozalvez, M. Sepulcre, M. Rondinone, R. Blokpoel, L. Lucken, and G. Thandavarayan, "Infrastructure support for cooperative maneuvers in connected and automated driving," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2019, pp. 20–25. doi: 10.1109/IVS.2019.8814044

[119] T. Kessler and A. Knoll, "Cooperative multi-vehicle behavior coordination for autonomous driving," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2019, pp. 1953–1960. doi: 10.1109/IVS.2019.8814060

[120] P. Pascheka and M. Düring, "Advanced cooperative decentralized decision making using a cooperative reward system," in *Proc. IEEE Int. Symp. Innov. Intell. Syst. Appl. (INISTA)*, Sep. 2015, pp. 1–7. doi: 10.1109/INISTA.2015.7276779

[121] K. Franke, M. Düring, R. Balaghiasefi, M. Gonter, K. Lemmer, and F. Kücükay, "A reference architecture for CISS/CDAS within the field of cooperative driving," in *Proc. IEEE Int. Conf. Connected Veh. Expo (ICCVE)*, Nov. 2014, pp. 357–363. doi: 10.1109/ICCVE.2014.7297571

[122] S. Aoki and R. Rajkumar, "A merging protocol for self-driving vehicles," in *Proc. ACM/IEEE Int. Conf. Cyber-Phys. Syst. (ICCPS)*, Apr. 2017, pp. 219–228. doi: 10.1145/3055004.3055028

[123] H. An and J.-i. Jung, "Design of a cooperative lane change protocol for a connected and automated vehicle based on an estimation of the communication delay," *Sensors*, vol. 18, no. 10, pp. 3499:1–3499:11, Oct. 2018. doi: 10.3390/s18103499

[124] D. Heß, R. Lattarulo, J. Pérez, J. Schindler, T. Hesse, and F. Köster, "Fast maneuver planning for cooperative automated vehicles," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 1625–1632. doi: 10.1109/ITSC.2018.8569791

[125] W. Xu, A. Willecke, M. Wegner, L. Wolf, and R. Kapitza, "Autonomous maneuver coordination via vehicular communication," in *Proc. Annu. IEEE/IFIP Int. Conf. Dependable Syst. Netw. Workshop (DSN-W)*, Jun. 2019, pp. 70–77. doi: 10.1109/DSN-W.2019.00022

[126] D. Maksimovski, C. Facchi, and A. Festag, "Priority maneuver (PriMa) coordination for connected and automated vehicles," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Sep. 2021, pp. 1083–1089. doi: 10.5220/0010442501000111

[127] W. Schwarting and P. Pascheka, "Recursive conflict resolution for cooperative motion planning in dynamic highway traffic," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2014, pp. 1039–1044. doi: 10.1109/ITSC.2014.6957825

[128] D. Lenz, T. Kessler, and A. Knoll, "Tactical cooperative planning for autonomous highway driving using monte-carlo tree search," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2016, pp. 447–453. doi: 10.1109/IVS.2016.7535424

[129] C. Peng and M. Tomizuka, "Cooperative driving based on negotiation with persuasion and concession," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2018, pp. 1118–1124. doi: 10.1109/IVS.2018.8500702

[130] C. Burger and M. Lauer, "Cooperative multiple vehicle trajectory planning using MIQP," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 602–607. doi: 10.1109/ITSC.2018.8569776

[131] M. Graf, O. Speidel, and K. Dietmayer, "Trajectory planning for automated vehicles in overtaking scenarios," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2019, pp. 1653–1659. doi: 10.1109/IVS.2019.8813854

[132] Z. Huang, D. Chu, C. Wu, and Y. He, "Path planning and cooperative control for automated vehicle platoon using hybrid automata," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 3, pp. 959–974, Mar. 2019. doi: 10.1109/TITS.2018.2841967

[133] B. Li, Y. Zhang, Y. Ge, Z. Shao, and P. Li, "Optimal control-based online motion planning for cooperative lane changes of connected and automated vehicles," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2017, pp. 3689–3694. doi: 10.1109/IROS.2017.8206215

[134] R. A. Brooks, "A robust layered control system for a mobile robot," *IEEE J. Robot. Autom.*, vol. RA-2, no. 1, pp. 14–23, Mar. 1986. doi: 10.1109/JRA.1986.1087032

[135] M. Werling, J. Ziegler, S. Kammel, and S. Thrun, "Optimal trajectory generation for dynamic street scenarios in a frenét frame," in *Proc. IEEE Int. Conf. Robot. Automat.*, May 2010, pp. 987–993. doi: 10.1109/ROBOT.2010.5509799

[136] H.-J. Günther, B. Mennenga, O. Trauer, R. Riebl, and L. Wolf, "Realizing collective perception in a vehicle," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2017, pp. 1–8. doi: 10.1109/VNC.2016.7835930

[137] J. B. Kenney, "Dedicated short-range communications (DSRC) standards in the United States," *Proc. IEEE*, vol. 99, no. 7, pp. 1162–1182, Jul. 2011. doi: 10.1109/JPROC.2011.2132790

[138] A. Festag, "Cooperative intelligent transport systems standards in Europe," *IEEE Commun. Mag.*, vol. 52, no. 12, pp. 166–172, Dec. 2014. doi: 10.1109/MCOM.2014.6979970

[139] K. Kiela, V. Barzdenas, M. Jurgo, V. Macaitis, J. Rafanavicius, A. Vasjanov, L. Kladovscikov, and R. Navickas, "Review of V2X-IoT standards and frameworks for ITS applications," *Appl. Sci.*, vol. 10, no. 12, pp. 4314:1–4314:23, Jun. 2020. doi: 10.3390/app10124314

[140] (2021, May) SAE International website. [Online]. Available: www.sae.org

[141] (2021, May) SAE International, V2X Communications Steering Committee website. [Online]. Available: www.sae.org/servlets/works/committeeHome.do?comtID=TEVCSC

[142] *Application Protocol and Requirements for Maneuver Sharing and Coordinating Service*, SAE Std. J3186, to be published.

[143] (2021, May) SAE International, Driver Assistance Systems Steering Committee website. [Online]. Available: www.sae.org/servlets/works/committeeHome.do?comtID=TEVSS3

[144] *Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles*, SAE Std. J3216, May 2020.

[145] *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, SAE Std. J3016, Jan. 2014.

[146] (2021, May) China Automotive Technology and Research Center Co, Ltd. website. [Online]. Available: www.catarc.ac.cn

[147] (2021, May) China Communications Standards Association website. [Online]. Available: www.ccsa.org.cn

[148] Ministry of Industry and Information Technology (MIIT), "Guideline for developing national Internet of vehicles standard system; intelligent connected vehicles," pp. 1–18, Dec. 2017. [Online]. Available: https://bit.ly/3kaMneT

[149] *Cooperative Intelligent Tranportation System; Vehicular Communication; Application Layer Specification and Data Exchange Standard*, C-SAE T/CSAE 53-2017, Sep. 2017.

[150] S. Chen, J. Hu, Y. Shi, L. Zhao, and W. Li, "A vision of C-V2X: Technologies, field testing, and challenges with Chinese development," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 3872–3881, Feb. 2020. doi: 10.1109/JIOT.2020.2974823

[151] (2021, May) European Telecommunications Standards Institute website. [Online]. Available: www.etsi.org

[152] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Maneuver Coordination Service*, ETSI TS 103 561, Rev. 0.0.1, Jan. 2018. [Online]. Available: https://bit.ly/3FcR43b

[153] *Intelligent Tranport Systems (ITS); Vehicular Communications; Informative Report for the Maneuver Coordination Service*, ETSI TR 103 578, Rev. 0.0.5, May 2020.

[154] *Intelligent Transport Systems (ITS); Cooperative Perception Services (CPS)*, ETSI TS 103 324, Rev. 0.0.19, Jul. 2020.

[155] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS);*, ETSI TR 103 562, Rev. 2.1.1, Dec. 2019.

[156] (2021, May) Intelligent Transport Society of Korea website. [Online]. Available: www.itskorea.kr

[157] Korea IT News. (2020, Jan.) South Korean government to enhance infrastructures for cooperative automated driving. [Online]. Available: https://english.etnews.com/20200130200001

[158] (2021, May) International Organization for Standardization website. [Online]. Available: www.iso.org

[159] (2021, May) ISO/TC 204, Intelligent Transport Systems website. [Online]. Available: www.iso.org/committee/54706.html

[160] *Intelligent Transport Systems – Evolved-Universal Terrestrial Radio Access Network – Part 3: LTE-V2X*, ISO Std. 17 515-3, Aug. 2019. [Online]. Available: www.iso.org/standard/73238.html

[161] (2021, May) Car-to-Car Communication Consortium website. [Online]. Available: www.car-2-car.org

[162] T. Kosch, I. Kulp, M. Bechler, M. Strassberger, B. Weyl, and R. Lasowski, "Communication architecture for cooperative systems in Europe," *IEEE Commun. Mag.*, vol. 47, pp. 116–125, May 2009. doi: 10.1109/MCOM.2009.4939287

[163] Car-to-Car Communication Consortium. (2021, May) Basic system profile. [Online]. Available: https://www.car-2-car.org/documents/basic-system-profile/

[164] (2021, May) Connected Motorcycle Consortium website. [Online]. Available: www.cmc-info.net

[165] (2020, Jul.) 5G Automotive Association website. [Online]. Available: www.5gaa.org

[166] "C-V2X use cases and service level requirements volume 2," 5G Automotive Association, Rep., Jan. 2021. [Online]. Available: https://bit.ly/3A2NSmL

[167] (2021, May) Next Generation Mobile Networks website. [Online]. Available: www.ngmn.org

[168] "V2X white paper," Next Generation Mobile Networks, White Paper, Jul. 2018. [Online]. Available: https://bit.ly/2RmKm32

[169] B. M. Masini, A. Bazzi, and A. Zanella, "A survey on the roadmap to mandate on-board connectivity and enable V2V-based vehicular sensor networks," *Sensors*, vol. 18, no. 7, pp. 2207:1–2207:18, Jul. 2018. doi: 10.3390/s18072207

[170] National Development and Reform Commission (NDRC), "Strategy for innovation and development of intelligent vehicles (Chinese)," pp. 3–12, Feb. 2020. [Online]. Available: https://bit.ly/327fzvP

[171] Ministry of Industry and Information Technology (MIIT), "Guideline for developing national Internet of vehicles standard system; intelligent vehicle management (Chinese)," pp. 1–17, Apr. 2020. [Online]. Available: https://bit.ly/35vvM1e

[172] M. Botte, L. Pariota, L. D'Acierno, and G. N. Bifulco, "An overview of cooperative driving in the European Union: Policies and practices," *Electron.*, vol. 8, no. 6, pp. 616:1–616:25, May 2019. doi: 10.3390/electronics8060616

[173] (2021, May) Co-operative Systems in Support of Networked Automated Driving by 2030 (AutoNet2030), 2013-2016, FP7-ICT, project website. [Online]. Available: www.cordis.europa.eu/project/id/610542

[174] (2021, May) Intelligente Manöver Automatisierung - Kooperative Gefahrenvermeidung in Echtzeit (IMAGinE), 2016-2022, bmwi, project website. [Online]. Available: www.imagine-online.de

[175] (2021, May) Transition Areas for Infrastructure-Assisted Driving (TransAID), 2017-2020, H2020, project website. [Online]. Available: www.transaid.eu

[176] (2021, May) Automated driving Progressed by Internet Of Things (AUTOPILOT), 2017-2020, H2020, project website. [Online]. Available: www.autopilot-project.eu/

[177] (2021, May) oneM2M project. [Online]. Available: www.onem2m.org

[178] G. Larini, G. Romano, M. Falcitelli, S. Noto, P. Pagano, M. Djurica, G. Karagiannis, and G. Solmaz, "Autonomous driving progressed by oneM2M: The experience of the AUTOPILOT project," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*. IEEE, Jun. 2019, pp. 204–208. doi: 10.1109/EuCNC.2019.8801948

[179] (2020, Jul.) 5G Communication Automotive Research and Innovation (5GCAR), 2017-2019, H2020, project website. [Online]. Available: www.5gcar.eu

[180] (2021, May) Crash Avoidance Metrics Partnership LLC website. [Online]. Available: www.campllc.org

[181] (2021, May) CAMP LLC Cooperative Automated Driving Systems Collaboration Project website. [Online]. Available: www.campllc.org/cooperative-automated-driving-systems-cads-collaboration-project/

[182] "Use of the 5.850–5.925 GHz band," Federal Communications Commission, First Rep. Order, Further Notice Proposed Rulemaking,

Order Proposed Modification, Nov. 2020. [Online]. Available: https://bit.ly/3kEKQko

[183] (2020, Jul.) 5G for Connected and Automated Road Mobility in the European Union (5G-CARMEN), 2018-2021, H2020, project website. [Online]. Available: www.5gcarmen.eu

[184] (2021, May) Strategic innovation promotion automated driving for universal services (SIP-adus), phase 2 2019-2022, website. [Online]. Available: www.sip-adus.go.jp

[185] "General data protection regulation," 2016/679, Eur. Parliament, Apr. 2016. [Online]. Available: https://bit.ly/3B6aqVc

[186] B. Häfner, J. Jiru, H. Schepker, G. A. Schmitt, and J. Ott, "Preventing failures of cooperative maneuvers among connected and automated vehicles," in *Proc. ACM Int. Conf. Model., Anal. Simul. Wireless Mobile Syst.*, Nov. 2021, pp. 5–12. doi: 10.1145/3479239.3485721

[187] H. Cao, S. Gangakhedkar, A. R. Ali, M. Gharba, and J. Eichinger, "A 5G V2X testbed for cooperative automated driving," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2016, pp. 1–4. doi: 10.1109/VNC.2016.7835939

[188] C. Campolo, A. Molinaro, F. Romeo, A. Bazzi, and A. O. Berthet, "5G NR V2X: On the impact of a flexible numerology on the autonomous sidelink mode," in *Proc. IEEE 5G World Forum (5GWF)*, Sep. 2019, pp. 102–107. doi: 10.1109/5GWF.2019.8911694

[189] L. Zhang, "Cooperative adaptive cruise control in mixed traffic with selective use of vehicle-to-vehicle communication," *IET Intell. Transp. Syst.*, vol. 12, no. 10, pp. 1243–1254, Jul. 2018. doi: 10.1049/iet-its.2018.5235

[190] C. Katrakazas, M. Quddus, W.-H. Chen, and L. Deka, "Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions," *Transp. Res. Part C: Emerg. Technol.*, vol. 60, pp. 416–442, Nov. 2015. doi: 10.1016/j.trc.2015.09.011

[191] B. Mirchevska, C. Pek, M. Werling, M. Althoff, and J. Boedecker, "High-level decision making for safe and reasonable autonomous lane changing using reinforcement learning," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 2156–2162. doi: 10.1109/ITSC.2018.8569448

[192] H. An and J.-i. Jung, "Decision-making system for lane change using deep reinforcement learning in connected and automated driving," *Electron.*, vol. 8, no. 5, pp. 543:1–543:13, May 2019. doi: 10.3390/electronics8050543

[193] I. Elleuch, A. Makni, and R. Bouaziz, "Cooperative overtaking assistance system based on V2V communications and RTDB," *Comp. J.*, vol. 62, no. 10, pp. 1426–1449, Apr. 2019. doi: 10.1093/comjnl/bxz026

[194] C. Adler, S. Eichler, T. Kosch, C. Schroth, and M. Strassberger, "Self-organized and context-adaptive information diffusion in vehicular ad hoc networks," in *Proc. IEEE Int. Symp. Wireless Commun. Syst. (ISWCS)*, Sep. 2006, pp. 307–311. doi: 10.1109/ISWCS.2006.4362309

[195] M. Sepulcre and J. Gozalvez, "On the importance of application requirements in cooperative vehicular communications," in *Proc. Annu. Conf. Wireless On-Demand Netw. Syst. Services (WONS)*, Jan. 2011, pp. 124–131. doi: 10.1109/WONS.2011.5720180

[196] R. Jacob, N. Franchi, and G. Fettweis, "Hybrid V2X communications: Multi-RAT as enabler for connected autonomous driving," in *Proc. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1370–1376. doi: 10.1109/PIMRC.2018.8580953

[197] M. Althoff, M. Koschi, and S. Manzinger, "CommonRoad: Composable benchmarks for motion planning on roads," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2017, pp. 719–726. doi: 10.1109/IVS.2017.7995802. [Online]. Available: commonroad.in.tum.de

[198] *Road Vehicles – Safety of the Intended Functionality*, ISO/PAS Std. 21 448, Jan. 2019. [Online]. Available: www.iso.org/standard/70939.html

[199] S. Söntges and M. Althoff, "Computing the drivable area of autonomous road vehicles in dynamic road scenes," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 6, pp. 1855–1866, Jun. 2018. doi: 10.1109/TITS.2017.2742141

[200] S. Manzinger and M. Althoff, "Negotiation of drivable areas of cooperative vehicles for conflict resolution," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2017, pp. 1–8. doi: 10.1109/ITSC.2017.8317765

[201] ——, "Tactical decision making for cooperative vehicles using reachable sets," in *Proc. IEEE Int. Conf. Intell. Transp. Syst. (ITSC)*, Nov. 2018, pp. 444–451. doi: 10.1109/ITSC.2018.8569560

[202] B. Brecht, D. Therriault, A. Weimerskirch, W. Whyte, V. Kumar, T. Hehn, and R. Goudy, "A security credential management system for V2X communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 12, pp. 3850–3871, Dec. 2018. doi: 10.1109/TITS.2018.2797529

[203] Q. Wang, D. Gao, and D. Chen, "Certificate revocation schemes in vehicular networks: A survey," *IEEE Access*, vol. 8, pp. 26 223–26 234, Jan. 2020. doi: 10.1109/ACCESS.2020.2970460

[204] M. Obst, L. Hobert, and P. Reisdorf, "Multi-sensor data fusion for checking plausibility of V2V communications by vision-based multiple-object tracking," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2014, pp. 143–150. doi: 10.1109/VNC.2014.7013333

[205] C. Allig, T. Leinmüller, P. Mittal, and G. Wanielik, "Trustworthiness estimation of entities within collective perception," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2019, pp. 1–8. doi: 10.1109/VNC48660.2019.9062796

[206] R. Shrestha, S. Y. Nam, R. Bajracharya, and S. Kim, "Evolution of V2X communication and integration of blockchain for security enhancements," *Electron.*, vol. 9, no. 9, pp. 1388:1–1388:33, Aug. 2020. doi: 10.3390/electronics9091338

Bernhard Häfner received the Master's degree in Electrical Engineering and Information Technology from Technical University of Munich (TUM), Germany in 2018. In the same year, he joined BMW Group and the Chair of Connected Mobility at TUM as a PhD candidate. His main research interests are cooperative maneuvers among automated vehicles, from enabling technologies to application-level protocols.

Vaibhav Bajpai is a senior researcher at Technical University of Munich, Germany. He received his PhD (2016) and Masters (2012) degrees in Computer Science from Jacobs University Bremen, Germany. He is the recipient of the best of CCR award (2019), ACM SIGCOMM best paper award (2018), and IEEE COMSOC award (2017) for the best dissertation in network and service management. His current research focuses on the performance and management of next-generation networked systems.

Jörg Ott holds the Chair of Connected Mobility at Technical University of Munich in the Faculty of Informatics since August 2015. He holds a PhD (1997) and a diploma in Computer Science (1991) from TU Berlin and a diploma in Industrial Engineering from TFH Berlin (1995). His research interests are in network architectures, (transport) protocols, and algorithms for connecting mobile nodes to the Internet and to each other. He explores edge and in-network computing as well as decentralized services. His research includes measuring and modeling human mobility and Internet usage as basis for design and evaluation.

Georg A. Schmitt received his diploma and Ph.D. degrees in Physics from Technical University of Munich in 1992 and 1996, respectively.

In 2012, he joined the BMW Group. He has worked as team lead in the area of charging infrastructure and standardization of charging interfaces, participating in and leading several German and EU INEA/CEF funded projects. Currently, he works as project lead responsible for vehicle connectivity technologies. He leads the activities on 5G and beyond cellular connectivity and ITS with focus on V2X solutions for automated and autonomous mobility.

Dr. Schmitt actively takes part in standardization within the ISO as well as industry associations like 5GAA or VDA.