A Survey on Decentralized Cooperative Maneuver Coordination for Connected and Automated Vehicles

Daniel Maksimovski[a], Andreas Festag*[b] and Christian Facchi[c]
Technische Hochschule Ingolstadt/ CARISSMA, Esplande 10, Ingolstadt, Germany

Keywords: V2X Communications, Cooperative Driving, Maneuver Coordination, Automated Vehicle.

Abstract: V2X communications can be applied for maneuver coordination of automated vehicles, where the vehicles exchange messages to inform each other of their driving intentions and to negotiate for joint maneuvers. For motion and maneuver planning of automated vehicles, the cooperative maneuver coordination extends the perception range of the sensors, enhances the planning horizon and allows complex interactions among the vehicles. For specific scenarios, various schemes for maneuver coordination of connected automated vehicles exist. Recently, several proposals for maneuver coordination have been made that address generic instead of specific scenarios and apply different schemes for the message exchange of driving intentions and maneuver negotiation. This paper presents use cases for maneuver coordination and classifies existing generic approaches for decentralized maneuver coordination considering implicit and explicit trajectory broadcast, cost values and space-time reservation. We systematically describe the approaches, compare them and derive future research topics.

1 INTRODUCTION

Automated and self-driving vehicles have the potential to reshape the automotive industry and mobility by improving the traffic safety and efficiency. In the last two decades, the research and development of advanced driver-assistance systems (ADAS) and automated driving functions have seen a huge increase, both in industry and academia.

Automated driving relies on on-board sensors that perceive the environment. Their limitations can be overcome by Vehicle-to-Everything (V2X) communications. V2X communication offers the possibility to extend the perception range and enhance the sensing of the vehicles by having a better representation of the environment. By exchanging driving intentions among vehicles, planning algorithms can enlarge their planning horizon and rely on direct information from other vehicles instead of predicting their behavior based on local sensor data. Finally, V2X communication allows for maneuver negotiation based on a bidirectional message exchange potentially with complex interactions.

V2X communication comprises the communication among vehicles, with pedestrians, the roadside infrastructure and networks. After several years of research, development and standardization, two access technologies are available for safety and traffic efficiency applications, i.e., WLAN-V2X (or ITS-G5 in Europe) and Cellular-V2X (Sjöberg et al., 2017; Molina-Masegosa and Gozalvez, 2017). Both operate in the 5.9 GHz frequency band allocated for road safety and traffic efficiency applications and enable a direct ad hoc communication among vehicles applicable for maneuver coordination.

The deployment of the V2X communications can be divided in three subsequent phases, in which applications with an increasing level of complexity and communication requirements are (or will be) implemented. In the first phase, "Day-1" applications exchange vehicle state information (position, speed, etc.) and share the occurrence of dangerous situations. They primarily cover applications for driver information and warning. In the European V2X communication system, these applications use the periodically broadcast Cooperative Awareness Message (CAM) (ETSI EN 302 637-2)[1] and the event-driven Decentralized Environmental Notification Message

[a] https://orcid.org/0000-0002-3414-1069
[b] https://orcid.org/0000-0001-5254-6425
[c] https://orcid.org/0000-0002-7762-9419
*Also with Fraunhofer Application Center for Connected Mobility and Infrastructure, Ingolstadt, Germany.

[1]ETSI standards are available at http://etsi.org.

Maksimovski, D., Festag, A. and Facchi, C.
A Survey on Decentralized Cooperative Maneuver Coordination for Connected and Automated Vehicles.
DOI: 10.5220/0010442501000111
In *Proceedings of the 7th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2021)*, pages 100-111
ISBN: 978-989-758-513-5
Copyright © 2021 by SCITEPRESS – Science and Technology Publications, Lda. All rights reserved

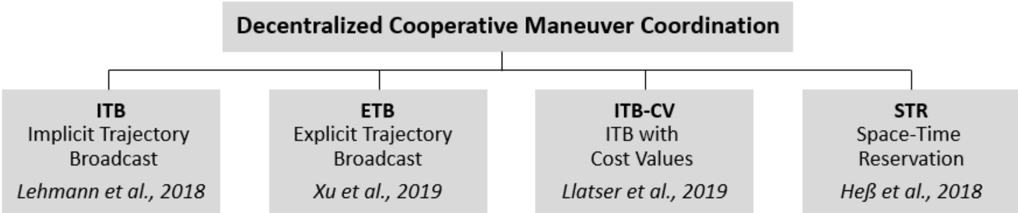


Figure 1: Classification of approaches for decentralized generic maneuver coordination.

(DENM) (ETSI EN 302 637-3). In the second phase, the "Day-2" applications rely on sharing of sensor data; more precisely on the exchange of detected objects in a vehicle's vicinity with the Collective Perception Messages (CPM), which is currently being standardized in ETSI (ETSI TR 102 562). In the third phase, the main emphasis is on the cooperative maneuver coordination between Connected and Automated Vehicles (CAVs). This coordination extends the other communication services by dedicated messages for the communication of the vehicle's maneuver intentions. While being a research topic, maneuver coordination is already considered in the early standardization process (e.g., draft ETSI TR 103 578).

Cooperative maneuver coordination aims at utilizing V2X communication for the coordination of maneuvers among vehicles in order to achieve safe and efficient driving. During this process, the involved CAVs exchange maneuver intentions that influence their driving behavior and agree on cooperative joint maneuvers based on each other needs in a negotiation phase with a defined number of coordination messages. The sharing of the intentions and coordination of maneuvers among the CAVs is expected to enhance the automated driving by avoiding conflicts or collision risks, and bring the deployment of fully driverless vehicles closer to reality.

Existing coordination approaches can mainly be categorized in two ways. The first one separates them into centralized and decentralized approaches. Centralized approaches have a central system that receives all the information and communicates the maneuvers with the respective vehicles. The decentralized approach does not consider a global planner entity, but is solely based on communication and coordination among the involved participants which can also consider a roadside unit (RSU). A hybrid approach considers both, the coordination among the CAVs and using a centralized system (typically RSU) to create a global plan for the vehicles. The other way of categorization is by implicit and explicit coordination. In implicit coordination, the CAVs share their intentions and desired maneuvers periodically and have to deduce from the changed intentions of the other CAVs whether their proposal has been accepted or not. Explicit coordination considers an explicit agreement with dedicated messages among the vehicles to perform an acknowledged maneuver in an event-based manner.

The present paper analyzes the state-of-the-art for decentralized maneuver coordination that involves only communication among the vehicles and does not include the RSUs. Considering the existing generic coordination approaches that are applicable to a wide range of scenarios, we classify them into four categories (Figure 1): Implicit Trajectory Broadcast (ITB), Explicit Trajectory Broadcast (ETB), Implicit Trajectory Broadcast with Cost Values (ITB-CV) and Space-Time Reservation (STR). For each category, we present and analyze the respective publication. Then, we compare these approaches and analyze commonalities and differences. From the review of the existing approaches, we derive future research topics. We regard our systematic review as a contribution for further research, standardization and development of maneuver coordination for connected automated driving.

The remainder of the paper is structured as follows. Section 2 presents cooperative driving use cases that benefit from maneuver coordination. The categories and the selected approaches for decentralized maneuver coordination are described in Section 3, followed by their discussion and comparison in Section 4, and a presentation of future research topics in Section 5. Section 6 concludes the paper.

2 USE CASES FOR MANEUVER COORDINATION

Cooperative driving brings many advantages for the automated vehicles to achieve more comfortable, safer and more efficient driving, as well as to optimize the traffic flow. It allows coordination of the maneuvers in more specific use cases that can cause conflicted and collision risk situations for the conventional and automated vehicles. Several cooperative use cases, where V2X communications can bring benefits and enable maneuver coordination, have been

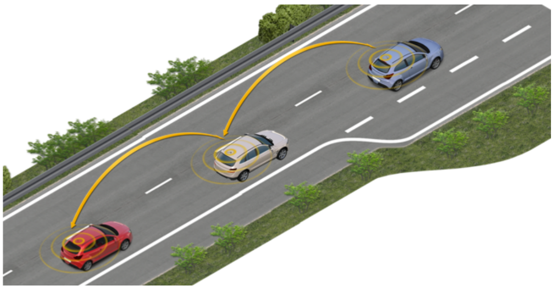


Figure 2: Cooperative ACC.

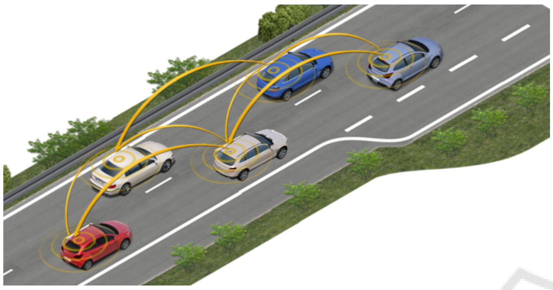


Figure 3: Cooperative driving in a convoy.

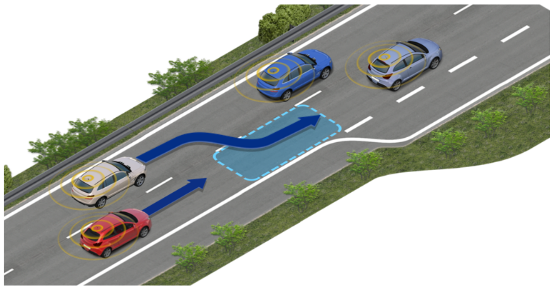


Figure 4: Cooperative lane change.

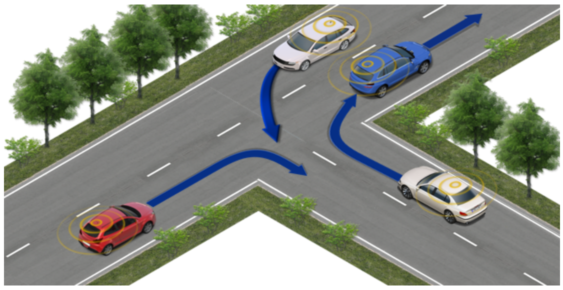


Figure 5: Cooperative driving at junction.

identified e.g., by the R&D projects AutoNet2030 and IMAGinE (Hobert et al., 2015; Llatser et al., 2019), and are summarized as follows:

Cooperative-ACC (C-ACC). This use case extends and improves the Adaptive Cruise Control (ACC) that allows the vehicles to exchange additional information using V2X to synchronize their velocities and avoid more frequent acceleration and braking and in the worst case, prevent critical situations (Figure 2). C-ACC can also be used to enable platooning.

Cooperative Driving in a Formation. Vehicles driving in a platoon or convoy are considered as part of formation driving. A platoon represents a group of vehicles in a same lane on a highway, usually truck platoons, that drive together in a stable formation keeping small distances between each other, hence increasing the road capacity, traffic comfort and efficiency. A platoon has a master, typically the leading vehicle, that coordinates maneuvers with the other vehicles and manages the platoon. Vehicles in a single or multi-line convoy (Figure 3) is another way to group the vehicles on highways. Instead of having a group leader, the vehicle control is distributed over all group vehicles in longitudinal and lateral direction resulting in vehicle disturbances affecting all of the convoy participants to a different extent; hence creating a stable formation. In a convoy, the vehicles only need the neighboring vehicles' dynamics information.

Cooperative Lane Change. In a cooperative lane change situation, the vehicles share their planned maneuver intentions and coordinate each other to successfully change the lane (Figure 4). The cooperative lane change maneuver can be executed between two vehicles or within a group of few vehicles in a safe and efficient manner.

Cooperative Driving in Non-signalized Intersections or Junctions. In intersections and junctions without signalization, CAVs can coordinate each other by exchanging their planned intentions and safely execute turning maneuvers (Figure 5).

Cooperative Overtaking. Cooperative overtaking is especially important on rural roads (Figure 6). Vehicles can exchange and coordinate their future planned trajectories to avoid a conflicted overtaking situation. It can also be exploited by heavily loaded trucks on highways to exchange their planned speed and current weight for optimal coordination.

Cooperative Lane Merging. Lane merging is a common maneuver on highways. Lane merging also occurs at construction site on the road. By exchanging their intentions, vehicles can assist each other to coordinate their merging maneuvers in a safe and efficient way (Figure 7).

Infrastructure-controlled Cooperative Driving. The infrastructure can plan the traffic distribution to optimize the traffic flow and exchange the global driving plan with the CAVs in different traffic situations. It can be used for traffic intersection management in both signalized and non-signalized intersections or junctions to optimize the traffic lights and to manage the intersection passing of each CAV, respectively (Figure 8). The infrastructure control can also be used to coordinate the cooperative lane merging.

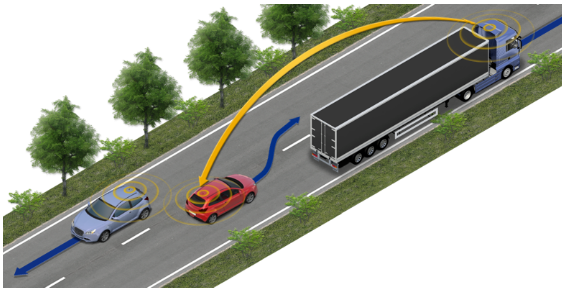


Figure 6: Cooperative overtaking.

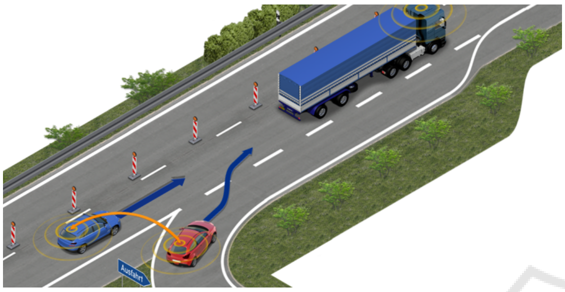


Figure 7: Cooperative lane merging.

3 DECENTRALIZED MANEUVER COORDINATION

In this context, the decentralized maneuver coordination depends solely on the communication among the CAVs to negotiate cooperative maneuvers. Furthermore, the coordination can be categorized into use case-specific and generic. In a use case-specific coordination, a coordination application is required that focuses only on one specific traffic situation, such as the ones presented in Section 2, and uses protocol only relevant to the respective use case. Generic coordination aims at using one protocol to solve all cooperative driving use cases.

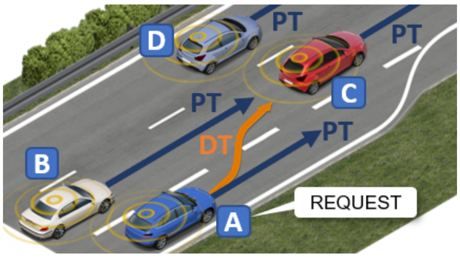
3.1 Use Case-specific Coordination Approaches

In order to solve the different traffic situations among the traffic participants as described in Section 2, a large number of research publications have contributed to various coordination protocols for specific use cases. Platooning (Vukadinovic et al., 2018) and C-ACC (Dey et al., 2016), which are based on longitudinal coordination and utilize communications among the vehicles, have been extensively investigated and numerous publications on their characteristics and control are available. Cooperative lane changing and merging situations require lateral and longitudinal coordination as vehicles also need to accelerate or decelerate in order to create the needed gap. Decentralized convoy driving allows the members of a convoy to keep a stable formation by adjusting their longitudinal and lateral dynamics and performing lane change maneuvers (Marjovi et al., 2015). Cooperative lane change service outside of a convoy as proposed in (Hobert et al., 2015) consists of a search, preparation and execution phase. The service supports maneuver negotiations and space reservations using dedicated broadcast lane change messages, i.e., request, response, prepared or abort messages in each of the three phases. C-AAC can also be used to achieve lane change and merging coordination, see (Bevly et al., 2016) for an overview. Distributed cooperative intersection and roundabouts management without the need for infrastructure support is analyzed in (Chen and Englund, 2016), discussing distributed resource reservation protocols using different message sets. Instead of use case-specific approaches, the review of the present paper focuses on generic approaches which will be presented next.

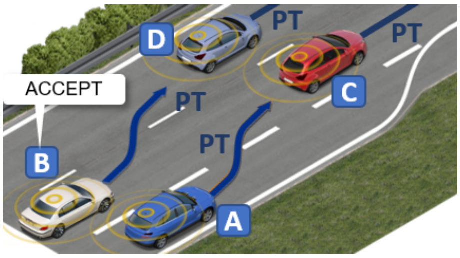
Figure 8: Cooperative intersection.

3.2 Generic Coordination Approaches

The generic decentralized coordination represents more recent state-of-the art approach considering maneuver coordination protocols that are independent of specific use case applications. They represent the most promising concepts for maneuver coordination and are presented in more detail in this work. Two types of implicit and explicit coordination protocols are discussed, as well as a hybrid approach incorporating infrastructure support for an already defined distributed protocol. The same lane merging scenario is used to describe the different protocol proposals consisting of four CAVs. The vehicles broadcast messages which consist of planned (PT), desired (DT), alternative (AT) and requested (RT) trajectories, as well as space-time reservation (STR). It is important to mention that details of how the aforementioned trajectories are planned and generated are not explained in the publications on trajectory broadcast

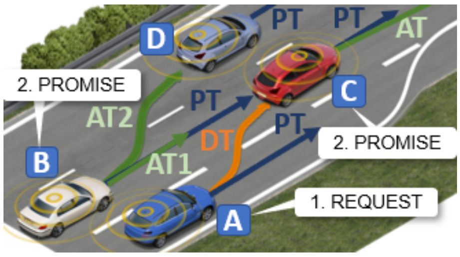


(a) Desired trajectory request

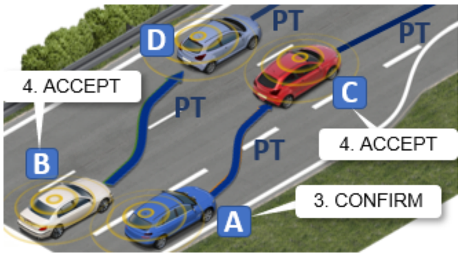


(b) Desired trajectory accepted

Figure 9: Maneuver coordination process in ITB.



(a) REQUEST and PROMISE



(b) CONFIRM

Figure 10: Maneuver coordination process in ETB.

approaches. In order to differentiate the unnamed different approaches, each of them is given a name and the corresponding abbreviations are used to address them (Figure 1).

3.2.1 Implicit Trajectory Broadcast (ITB)

The first generic maneuver coordination protocol was proposed by (Lehmann et al., 2018). It defines a new message type, i.e., the Maneuver Coordination Message (MCM) that carries trajectory information. In the MCM, the data elements for trajectories are represented as Frenét frames; a format that is commonly used for trajectories along a geometric shape. The vehicles periodically broadcast their planned trajectories (PT) and optionally a desired trajectory (DT). The latter represents an alternative, more preferred trajectory that is currently hindered by another vehicle due to the right-of-way rules. In order to complete the maneuver coordination, this work identifies the following three phases: detection, negotiation and execution.

Considering the lane merging scenario in Figure 9, vehicle A detects the need for a lane merging maneuver and shares its DT that currently intersects with the PT of vehicle B (Figure 9a); in this way the negotiation phase is started. After its own assessment, vehicle B decides whether to accept or ignore the request. In this situation, B accepts, adapts and broadcasts its new PT. This enables the requesting vehicle A to execute its DT, which is now adapted into PT (Figure 9b).

In this implicit approach, the accepting vehicle acknowledges that it accepts the requested DT by broadcasting its new adapted PT, but does not explicitly refer to a specific request. It is also required that each vehicle that receives the DT broadcast has to determine whether its future planned maneuver intersects this trajectory or not. In this situation, vehicles C and D do not intersect the DT.

3.2.2 Explicit Trajectory Broadcast (ETB)

The idea of ITB was extended with a concrete explicit coordination protocol that is also based on the principle of detection, negotiation and execution (Xu et al., 2019). The emphasis is on the negotiation protocol, which introduces a set of three message types: REQUEST, PROMISE and CONFIRM. These messages can be considered as MCM types and are broadcast during the negotiation phase. They can carry multiple trajectories in parallel, in contrast to ITB that considers only one trajectory at a time. The protocol is explained in the lane merging scenario in Figure 10 and the messages are also numbered to indicate their order.

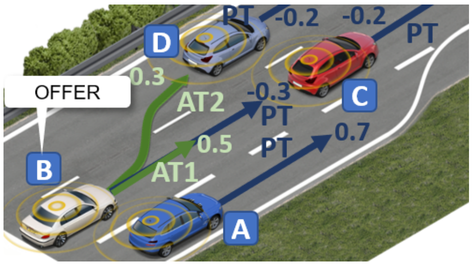
After vehicle A detected a need for cooperation, it broadcasts a REQUEST message, which can consist of multiple DTs. Multiple requests to different vehicles are possible, too. In this situation, vehicles B and C hinder this DT and after the DT request is received, they decide whether to accept it or not. If the accepting vehicles are able to plan collision-free trajectories, they can send multiple alternative trajectories (AT) in a PROMISE message (Figure 10a). The requesting vehicle A constructs a collision-free global plan for all of the participants and sends it via a CONFIRM message. After that, in order to execute the desired maneuver, the requesting vehicle needs one more broadcast message from the accepting vehicles that shows that the vehicles adapted the promised PTs. If the accepting vehicles adapt their PTs as promised, the coordination process is successful (Figure 10b), otherwise after a certain timeout the requesting vehicle can abort the coordination if one or all of the participating vehicles are not able to adapt their promised PTs because of different reasons. The vehicles are also not allowed to send different PROMISE and CONFIRM messages within a certain period of time. In this way, the protocol prevents potential ambiguities and risk of divergence, which means that vehicles will not end up choosing contradictory plans.

(Xu et al., 2019) also discuss communication failures, since the protocol does not assume a reliable message transmission. In case of message loss, the most important message is the CONFIRM message. If any communication failure happens before, none of the vehicles are going to change their trajectories. The only problem can arise if the CONFIRM message is delivered to a subset of vehicles. In the described scenario, if the message is delivered to B, but not to C, B will be the only vehicle to change the trajectory. This can cause overhead but will not lead to a worse situation because the PROMISE and CONFIRM messages have the requirement that only collision-free trajectories can be included.

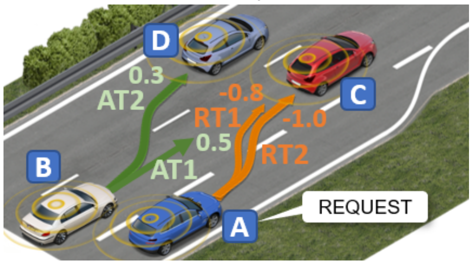
3.2.3 Implicit Trajectory Broadcast with Cost Values (ITB-CV)

(Llatser et al., 2019) propose an implicit coordination approach by periodically exchanging trajectories with cost values. Similar to ITB, it relies on MCM as the message type but assigns the cost values as additional trajectory attributes that express the necessity and willingness of the CAVs for cooperation. The proposed MCM format consists of three containers describing the basic message information, the current position of the vehicle and the trajectory information. The cooperation protocol is explained in the lane change scenario in Figure 11.

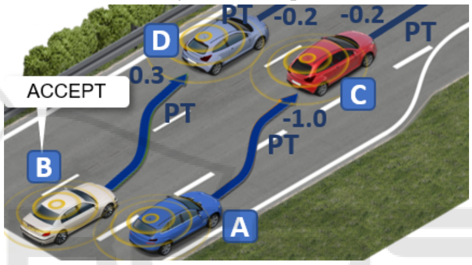
The protocol considers three different types of trajectories: reference (PT), alternative (AT) and requested (RT) trajectory. Each CAV sends its PT with a cost value, representing its future planned trajectory. In this situation, the PT of vehicle A has a cost value $C = 0.7$. This means, A has a necessity to cooperate since $C > 0$. The PT of the vehicle B has a cost value of -0.2, indicating it is willing to cooperate with other vehicles, because $C < 0$. If $C = 0$, the vehicle does not have a necessity nor willingness to cooperate. B sees the need of A and offers two ATs with cost values 0.3 and 0.5 (Figure 11a). By definition, these costs are higher than the reference cost because in order to execute them, a coordination is necessary. After A receives the ATs which represent an offer from B, it sends two RTs with high willingness costs: -1.0 and -0.8 (Figure 11b). The accepting vehicle B constructs a global plan for both vehicles by selecting its own trajectory and the trajectory for the requesting vehicle A that gives the lowest total cost. Finally, the selected trajectories are adapted as PTs and the cooperation is successfully completed (Figure 11c).



(a) Alternative trajectories offer



(b) Trajectories request



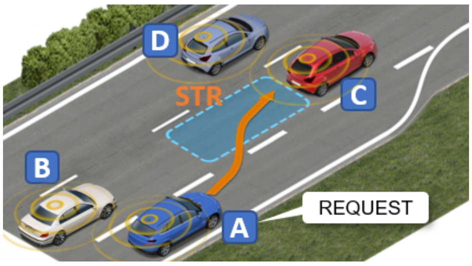
(c) Request accepted

Figure 11: Maneuver coordination process in ITB-CV.

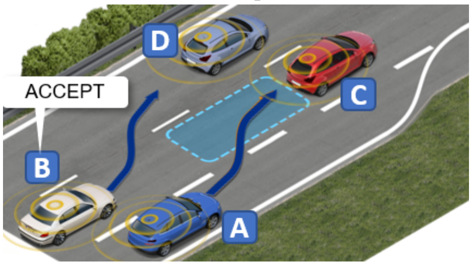
3.2.4 Space-Time Reservation (STR)

The space-time reservation protocol (Heß et al., 2018; Nichting et al., 2019; Heß et al., 2019) is a different approach than ITB and ETB. It is not based on trajectories exchange and request, but rather on an explicit reservation of position and time constraints among the communicating vehicles. This work merges a nominal maneuver planner for autonomous driving with a cooperative driving protocol. The space-time constraints are only exchanged once the need for cooperation is identified using the containers of a CAM message, hence using fewer messages with simple reservation encoding.

SCITEPRESS SCIENCE AND TECHNOLOGY PUBLICATIONS



(a) STR request



(b) STR accepted

Figure 12: Maneuver coordination process in STR.

In the lane change scenario in Figure 12, vehicle A sends a REQUEST message that consists of the STR constraints set with the following parameters: position where the reservation should start, length of the reserved area, time interval, velocity, ID of the requesting vehicle and a reference to the corresponding request (Figure 12a). If the accepting vehicles can plan a collision-free maneuver incorporating these constraints, they send a COMMIT message (Figure 12b). A REJECT message is sent if the vehicles can not or does not want to accept the request. In case the plans for the requesting vehicle changed, it can also cancel the request. Figure 12 shows the trajectories for better visibility; we note that they are not periodically broadcast among the vehicles.

3.2.5 Infrastructure Support for Decentralized Coordination

(Correa et al., 2019) present an enhancement of the proposed ITB approach to consider infrastructure support. Road side unit (RSU) information is included in the MCM format alongside the proposed trajectories exchange information between the vehicles. In this way the infrastructure can support the CAVs by offering advice on proposed speed, gap, lane or transition of control between the automated system and the driver using vehicle-to-infrastructure communications (Figure 8). This approach can lead to a more neutral coordination, enhanced perception and coordination involving multiple vehicles in specific traffic situations.

4 COMPARISON OF APPROACHES

Table 1 shows a comparison of the presented decentralized generic approaches using different criteria. Since results from a performance evaluation are not available for all of the described approaches or – if available – the results are not comparable, the comparison is based on the conceptual design of the proposed coordination protocols and on an analysis of their advantages and shortcomings.

The ITB approach (Lehmann et al., 2018) brings a lot of novelties, in particular the broadcast of planned and desired trajectories, Maneuver Coordination Service with Maneuver Coordination Messages focusing only on the exchange of trajectories, as well as using the Frenét frames as standardized way to represent the trajectories. However, considering more vehicles, this protocol can result in ambiguities due to its implicitness. In a situation with only two vehicles, the protocol can still cause conflicts due to the fact that it is not known if the accepting vehicle changes its PT due to the given request or because of another request. It is also a serial coordination approach, meaning that at a time the vehicles can only negotiate one trajectory. This brings advantage in terms of reducing the motion planning system complexity. However, a successful coordination might require several requests, meaning longer time to find an acceptable DT. Considering all these aspects, this concept stands as a solid basis for cooperative maneuver coordination.

ETB (Xu et al., 2019) further improves the ETB approach by proposing an explicit coordination with a defined number of negotiation messages that limits communication failures and eliminates protocol ambiguities. The approach also considers negotiation of multiple trajectories and cooperation between more than two vehicles. However, due to the higher number of negotiation messages, the probability of communication failures is also increased.

The ITB-CV approach (Llatser et al., 2019) brings an additional information to the trajectories by using cost values that help the requesting vehicles to show the extent of their need for cooperation. It also helps the accepting vehicle to decide whether to accept or reject a given request. However, the addition of a cost value to each reference trajectory results in a higher algorithmic complexity for the motion planning system, as it needs to be computed at each time step. Since it is an implicit approach, the coordination process introduces the same ambiguities as in the ITB approach. Also, compared to ETB, the impact of communication failures will be larger because the message losses can cause further ambiguities too.

Table 1: Comparison of generic approaches for decentralized maneuver coordination (BC = Broadcast, TR = Trajectory).

	ITB (Lehmann et al., 2018)	**ETB** (Xu et al., 2019)	**ITB-CV** (Llatser et al., 2019)	**STR** (Heß et al., 2018)
Coordination type	implicit	explicit	implicit	explicit
Serial or parallel	serial	parallel	parallel	parallel
Number of vehicles	2	more than 2	2	more than 2
Communication type	periodic BC	periodic BC	periodic BC	non-periodic BC
Message type	MCM	MCM	MCM	CAM
Number of messages	2	4	3	2
Request method	desired TR	desired TR	requested TR	space-time
Protocol ambiguities	yes	no	yes	no
Impact of comm. failures	yes	limited	yes	limited
Simulation results	no	yes	no	yes
Experimental results	no	no	no	yes

A reservation of position and time constraints proposed by the STR approach (Heß et al., 2018) offers certain flexibility as – in contrast to the other trajectory request approaches – the requesting vehicle can modify its planned trajectory within the reserved area. The other main difference is the fact that the negotiation is simpler because the accepting vehicles do not broadcast their maneuver intentions. Once the accepting vehicles commit to the request, for the given time they cannot intersect the requested constraints. (Heß et al., 2018) is also the only publication that integrates the coordination process with an automated motion planning system and validates the approach in a real test environment using real test vehicles. Furthermore, it is the only approach that uses an extended CAM message only when the coordination need is detected, hence requires the lowest bandwidth which is another advantage in comparison with the other approaches that propose the periodic broadcast of a separate MCM message.

The first three approaches utilize the broadcast of trajectories, which improves the prediction system of the CAVs. The best prediction of the other vehicles movements is using their shared planned trajectory, which reduces the uncertainty and improves the safety in many difficult or critical situations. By knowing the intentions of the other vehicles, the CAVs will be able to solve many situations. Disadvantages come with the high data rate of periodic broadcasting and the many implementation and communication issues that need to be solved. The possibility to find a faster and more suitable solution increases with the parallel approaches that allow negotiation of multiple trajectories at a time between the vehicles; however the algorithmic complexity of the motion planning system also grows.

The implicit approaches might be an easier solution to implement in a simpler case with only two co-operating vehicles because more difficult situations or more vehicles can bring various protocol and communication failure ambiguities. In comparison, the explicit approaches allow coordination between more vehicles with limited impact of the communication failures and no protocol ambiguities which makes it a much safer solution that prevents conflicted situations and additional risks. To enable fast, safe, efficient and unambiguous coordination for the cooperative vehicles, the type and number of negotiation messages play a crucial role. Table 1 shows the minimum required messages that allow the requesting vehicle to execute the desired maneuver. This considers that the coordination succeeds at first try and all messages are broadcast only once. The negotiation protocol proposed in the ETB approach enables safe and unambiguous coordination with multiple options and more than two included vehicles, but it also requires the largest number of exchanged messages. The STR approach allows for fast explicit coordination with two messages where the requesting vehicle does not need to know the adapted trajectories of the other vehicles. However, this might introduce ambiguity and some overhead in the movement of the other participants, especially in a more complex traffic situation with many vehicles included because it does not include a final confirm message such as in ETB. A CONFIRM message ensures that the selected trajectories of all participating vehicles will not conflict.

Additional analysis is required to show the impact of the presented approaches on the traffic efficiency. The ETB approach used the vehicular networking simulation framework Artery[2] and evaluated the loss of time caused by driving below the ideal speed in a simple highway lane merging scenario. The results have shown that the total time loss for the communicating vehicles can be reduced up to 50% compared

[2]https://github.com/riebl/artery

to non-communicating vehicles. The presented approaches also need to prove that they can prevent any additional safety risks introduced by the maneuver coordination process and validate the safety of the protocol using different metrics. (Correa et al., 2019) performed a simulation in the microscopic traffic simulator SUMO[3], which showed that this approach could significantly increase the safety by reducing the time-to-collision (TTC) events with less than 3 s. In addition to the TTC, other safety metrics can be used such as the Post Encroachment Time (PET) metric that describes how dangerous a certain situation can be.

All of the presented decentralized approaches include only a single requesting vehicle to initiate the coordination process and the other vehicles need to adapt based on their needs. The infrastructure support could help to provide more neutral coordination in certain situations; a joint maneuver negotiation process with more initiating vehicles can be considered too. The more complex cascading process, where vehicles need to send another maneuver request in order to accept an incoming request, is avoided too.

5 OPEN TOPICS FOR DECENTRALIZED MANEUVER COORDINATION

The review and discussion in the previous sections have shown that several approaches with different characteristics exist. This section presents further research gaps related to the detection and decision logic, to the protocol and to V2X communications.

5.1 Detection and Decision Logic

How to Detect a Maneuver Coordination Need? The reviewed approaches discuss only what happens after the need for cooperation has been recognized and the detection process is not described. An algorithm is required that perceives the surrounding CAVs hindering the desired maneuver and decides when an alternative, more suitable and feasible maneuver should be requested. Different metrics could be used to take a decision such as improving the time efficiency and avoiding safety-critical situation in a worst-case scenario. Mixed traffic scenarios with communicating and non-communicating vehicles should also be investigated, since the presented approaches consider only situations involving CAVs.

How to Decide whether to Accept or Reject a Maneuver Coordination Request? The best and easiest situation for a maneuver coordination is the one that is beneficial for all of the included vehicles. Since in most of the situations one vehicle will be disadvantaged, the evaluation of the situation and request is very important for the accepting vehicle and an appropriate assessment is required. In (Düring and Pascheka, 2014), different types of cooperative and uncooperative behavior are defined based on a total utility function. Metrics or cost functions considering loss of time, required deceleration and velocity or potential safety critical consequences can be used to decide whether to accept or reject a request in certain traffic situations.

5.2 Maneuver Coordination Protocol

Is an Application-independent, Robust Representation of Trajectories Possible? Communicated trajectories need to be correctly interpreted at both, the requesting and accepting vehicles. It needs to be independent from specific applications and a situation analysis system is needed to correctly represent the trajectories in the environmental model of a CAV. Falsely interpreted or inaccurate trajectory-related data can lead to conflicted negotiation outcome for the involved vehicles and introduce safety critical situations.

Can the Number of Involved Vehicles Be Increased? A coordination between two vehicles appears as a promising approach. Considering the probability of successful cooperation and communication failures, a coordination involving three or more vehicles leads to a considerably higher complexity and the protocols need to specify the number of vehicles that could potentially cooperate in more difficult traffic scenarios. The current approaches have no upper bound on the potential number of included vehicles and the scalability of the coordination in different traffic scenarios requires further analysis.

What Kind of Message Type and Format has to be Used? Most of the existing approaches propose a new, dedicated message type (MCM) for the exchange of trajectory-related information among the vehicles. RSU maneuver container in the MCM format is also discussed to incorporate the infrastructure support in specific situations, in this way utilizing vehicle-to-infrastructure communications to enhance the coordination process. The required standardized format of trajectory representation will very much depend on the data carried by the MCMs.

How Many Coordination Messages are Required? Fast, safe, unambiguous and efficient coordination requires a certain fixed number of negotiation messages

[3]https://www.eclipse.org/sumo

for each situation. Each coordination requires at least a request and an acceptance or rejection message. Final decision message such as the presented CONFIRM message (Xu et al., 2019) also ensures that the coordination will be executed as planned. Additional messages in specific situations might also be considered such as cancel message, if the requesting vehicle decides to cancel the request, or abort message in a situation when the requesting or accepting vehicle, due to specific reasons, aborts an already agreed maneuver in the execution phase.

Can Use Case-specific Application Messages Be Included? The proposed generic approaches cover several cooperative maneuver coordination use cases but some might need additional use case-specific information. For this purpose, a generic protocol should be able to incorporate application-specific messages. Such type of messages could be required for the management of vehicles driving in a platoon or convoy, or to request additional information required for the completion of a specific maneuver such as the right timing to perform a cooperative overtaking maneuver on a rural road.

Which Message Generation Rules Can Be Identified? These rules define when and which vehicle should send a message. They can have a huge impact on the effectiveness of the coordination process and data traffic in general. Some of the reviewed approaches propose periodic broadcast, but the exact interval is not defined. Similar to CAM and CPM, dynamic generation rules for maneuver coordination messages could be considered where the message interval depends on the vehicle dynamics, i.e., speed, heading and acceleration.

How Can Cascading Be Enabled? Maneuver cascading has so far been avoided by the presented decentralized approaches. It can help in many traffic situations to realize a requested maneuver. The accepting vehicle needs to request a maneuver itself to another adjacent vehicle. If this additional maneuver is successful, assuming that the current driving situation did not change significantly, it will enable the initial requesting vehicle to execute its desired maneuver. It can also be seen as an explicit maneuver coordination between more than two vehicles, which will include additional negotiation messages. Such a cascading maneuver will prolong the negotiation process and will bring additional complexity, but it can eventually increase the probability of a successful coordination. A further analysis is needed to show whether such a maneuver can be safe and efficient enough to be considered as an addition to the coordination protocol in specific situations.

Can the Data Security and Privacy Be Guaranteed? It can be presumed that maneuver coordination will apply digital signatures and certificates of the V2X communication system that provides integrity, authentication and non-repudiation of the exchanged messages. Still, open challenges exist, e.g. for misbehavior detection and mitigation as an application-specific security mechanism. Similarly, privacy will be expected to rely on short-living and changing pseudonyms. However, pseudonyms must not be changed during a maneuver since it is a safety-critical situation. Also, the small number of vehicles involved in a maneuver may undermine the anonymity since the requesting or accepting vehicle may be identifiable.

5.3 V2X Communications

What are the Communication Requirements for Maneuver Coordination? So far, the V2X communication system has been primarily designed for driver information and warnings with relaxed communication requirements. It is commonly accepted that safety-critical communications such as maneuver coordination require very low latency ($\sim 10\,\text{ms}$) and very high communication reliability ($> 99\,\%$) (Boban et al., 2018). The specific requirements for the exchange of multiple subsequent messages are not yet well understood since most of the existing work refers to individually broadcast messages.

Can Advanced Features of the Underlying Access Technology Be Exploited? WLAN-V2X and Cellular-V2X have been widely studied and their potential benefit for safety applications is well investigated. It is still to be seen whether the specific advanced features in Cellular V2X translate it into improved performance for maneuver coordination. One example of these features is the bounded latency of Sensing-based Semi-Persistent Scheduling (SB-SPS) in Cellular-C2X in scenarios with a high network load. Also, it is to be investigated whether the evolution of the access technologies, incl. IEEE 802.11bd and 5G NR V2X bring advantages, e.g. for the reliability or the latency of the message exchange.

Will Broadcast Communication Prevail? V2X communication is primarily based on broadcast communication, more specifically single-hop broadcast or (in the European V2X system) multi-hop broadcast within a defined geographical area. By design, broadcast does not provide reliable message exchange since the feedback implosion prevents applying acknowledgements and re-transmissions. The message exchange for cooperative maneuver coordination typically involves only few vehicles and may facilitate other approaches than broadcast, e.g., small-group multicast with explicit acknowledgment that increases the reliability.

Should Multi-channel Operation Be Applied? A higher number of messages increases the channel load, which results in a lower reliability and longer latency. In order to reduce the risk of channel congestion, an analysis is required whether the MCMs should be integrated on the same channel with other messages with a prioritization among the messages, or a multi-channel option should be considered.

6 CONCLUSION

Maneuver coordination using V2X communications targets at safer, more comfortable and efficient driving for CAVs. Generic approaches for maneuver coordination can be identified as a research trend. These approaches solve different traffic situations by a scenario-independent solution. In the present paper, existing proposals were reviewed and analyzed. Also, seven use cases, for which maneuver coordination is expected to bring benefits, were presented, ranging from C-ACC to infrastructure-controlled cooperative driving. In order to explain the differences and novelties, the existing generic approaches for decentralized coordination were described in detail for a lane merging scenario as an example use case. The approaches were classified into four categories: Implicit Trajectory Broadcast (ITB), Explicit Trajectory Broadcast (ETB), ITB with Cost Values (ITB-CV) and Space-Time Reservation (STR).

The analysis and discussion of the proposed protocols in the paper has shown that explicit maneuver negotiation and broadcast of future maneuver intentions can enable safe and efficient maneuver coordination. Further analysis is needed to evaluate the impact of the proposed approaches on traffic safety and efficiency. The introduction of additional safety risks needs to be eliminated. Well-defined metrics for traffic safety and efficiency should be considered to assess the performance. In the paper, challenges were highlighted and future research directions identified. These include the detection and decision logic of maneuvers, syntax and semantic of the maneuver protocol as well as reliability mechanisms of the V2X protocol. The key research question is: How can a use case-independent, reliable and low-latency protocol for safe, comfortable and efficient maneuver coordination be designed?

ACKNOWLEDGEMENTS

This work was gratefully supported by the German Science Foundation (DFG) by project KOALA 2 under number 273374642 within the priority program Cooperatively Interacting Automobiles (CoInCar, SPP 1835). The authors thank Daniel Heß (DLR) and Alexey Vinel (Halmstad University) for valuable discussions. The scenario figures in the paper were created with the illustration toolkit from the C2C-CC.[4]

REFERENCES

Bevly, D. et al. (2016). Lane change and merge maneuvers for connected and automated vehicles: A survey. *IEEE Transactions on Intelligent Vehicles*, 1(1):105–120.

Boban, M., Kousaridas, A., Manolakis, K., Eichinger, J., and Xu, W. (2018). Connected roads of the future: Use cases, requirements, and design considerations for vehicle-to-everything communications. *IEEE Vehicular Technology Magazine*, 13(3):110–123.

Chen, L. and Englund, C. (2016). Cooperative intersection management: A survey. *IEEE Transactions on Intelligent Transportation Systems*, 17(2):570–586.

Correa, A. et al. (2019). Infrastructure support for cooperative maneuvers in connected and automated driving. In *2019 IEEE IV Symposium*, pages 20–25.

Dey, K. C. et al. (2016). A review of communication, driver characteristics, and controls aspects of Cooperative Adaptive Cruise Control (CACC). *IEEE Transactions on Intelligent Transportation Systems*, 17(2):491–509.

Düring, M. and Pascheka, P. (2014). Cooperative decentralized decision making for conflict resolution among autonomous agents. In *2014 IEEE INISTA*, pages 154–161.

Heß, D., Lattarulo, R., Pérez, J., Hesse, T., and Köster, F. (2019). Negotiation of cooperative maneuvers for automated vehicles: Experimental results. In *2019 IEEE ITSC*, pages 1545–1551.

Heß, D., Lattarulo, R., Pérez, J., Schindler, J., Hesse, T., and Köster, F. (2018). Fast maneuver planning for cooperative automated vehicles. In *2018 ITSC*, pages 1625–1632.

Hobert, L. et al. (2015). Enhancements of V2X communication in support of cooperative autonomous driving. *IEEE Communications Magazine*, 53(12):64–70.

Lehmann, B., Günther, H., and Wolf, L. (2018). A generic approach towards maneuver coordination for automated vehicles. In *2018 ITSC*, pages 3333–3339.

Llatser, I., Michalke, T., Dolgov, M., Wildschütte, F., and Fuchs, H. (2019). Cooperative automated driving use cases for 5G V2X communication. In *2019 IEEE 2nd 5G World Forum*, pages 120–125.

[4]URL: http://https://www.car-2-car.org

Marjovi, A., Vasic, M., Lemaitre, J., and Martinoli, A. (2015). Distributed graph-based convoy control for networked intelligent vehicles. In *2015 IEEE IV Symposium*, pages 138–143.

Molina-Masegosa, R. and Gozalvez, J. (2017). LTE-V for sidelink 5G V2X vehicular communications: A new 5G technology for short-range vehicle-to-everything communications. *IEEE Vehicular Technology Magazine*, 12(4):30–39.

Nichting, M., Heß, D., Schindler, J., Hesse, T., and Köster, F. (2019). Explicit negotiation method for cooperative automated vehicles. In *2019 ICVES*, pages 1–7.

Sjöberg, K., Andres, P., Buburuzan, T., and Brakemeier, A. (2017). Cooperative Intelligent Transport Systems in Europe: Current deployment status and outlook. *IEEE Vehicular Technology Magazine*, 12(2):89–97.

Vukadinovic, V. et al. (2018). 3GPP C-V2X and IEEE 802.11p for vehicle-to-vehicle communications in highway platooning scenarios. *Elsevir Ad Hoc Networks*, 74:17 – 29.

Xu, W., Willecke, A., Wegner, M., Wolf, L., and Kapitza, R. (2019). Autonomous maneuver coordination via vehicular communication. In *2019 IEEE/IFIP DSN-W*, pages 70–77.

SCITEPRESS
SCIENCE AND TECHNOLOGY PUBLICATIONS