2018 21st International Conference on Intelligent Transportation Systems (ITSC)
Maui, Hawaii, USA, November 4-7, 2018

A Generic Approach towards Maneuver Coordination for Automated Vehicles

Bernd Lehmann[1], Hendrik-Jörn Günther[2] and Lars Wolf[3]

Abstract— **Increasing the predictability of traffic participants is the key for developing safe Automated Vehicles (AVs). Whereas most research focuses on enhanced environment perception and vehicle trajectory planning methodologies, this contribution proposes a generic concept employing inter-vehicle communications to coordinate maneuvers of AVs. Not targeting a specific application, the concept is based on a generic description of vehicle behaviors, leveraging the well-known concept of Frénet frames. By sharing a vehicle's *planned maneuver* with surrounding traffic participants, inter-vehicle communications reduces the uncertainty associated to the prediction of future vehicle maneuvers. In case of conflicting maneuvers, vehicles are given the opportunity to disseminate a *desired trajectory* in addition to its *planned trajectory*. Maneuver coordination is then established in a three-step implicit distributed fashion, based on common right-of-way rules and on both disseminated types of trajectories. Next to the introduction of the maneuver coordination process, this contribution elaborates on related research questions and provides an outlook on an extension to a well-known microscopic simulation environment to analyze effects of the maneuver coordination process on inter-vehicle communications and traffic efficiency. The proposed concept aims at providing a generic concept to reach coordination between Connected and Automated Vehicles (CAVs).**

Index Terms— **Cooperative Driving, Trajectory, V2V Communications**

I. Introduction

AVs have been a topic of research for quite some time and are believed to not only increase comfort for the passengers but also to increase road safety [1]. From 2003 onwards, the Defense Advanced Research Projects Agency (DARPA) challenges intensified research in different areas of automatically driving vehicles [2]. The core architecture of AVs is based on the triad of *sensing* the environment, *planning* the vehicle's path and *acting* according to this path. Extensive research and development activities can be observed for all three aspects.

The 2007 DARPA Urban Challenge addressed automated driving in an urban environment, in which the AVs not only had to plan their own trajectory — but also had to adapt and react to other traffic participants and automated vehicles. Similar to the task of today's drivers, AVs have to adapt their trajectories to (observable) external constraints while still achieving their own (unobservable) objectives. With the advent of inter-vehicle communications, CAVs are provided the opportunity to share the unobservable factors as well. Vehicle-to-X (V2X) communications provides means to improve the environment perception of CAVs by exchanging a vehicle's current dynamic state and its perceived objects [3, 4]. This contribution leverages inter-vehicle communications to also exchange the intentions of a CAV such as its planned driving maneuver. Although applicable to mixed traffic, it is first assumed that all vehicles involved in a maneuver coordination process are capable of sharing their behavior by means of V2X communications.

Most of the concepts for sharing information about a vehicle's planned behavior are based on extensive protocols addressing very specific traffic situations and applications only, e.g. merging, Cooperative Adaptive Cruise Control (C-ACC) and alike. In contrast, we propose a generic approach for maneuver coordination to promote *cooperative behavior*[1] as defined by Düring and Pascheka [5]. Rather than sharing information in a specific traffic situation only, our concept aims at continuously exchanging the future behavior of a CAV composed of the following two components: the *planned trajectory*, which is the current trajectory of the CAV, as well as the *desired trajectory* resulting from an alternative planning process representing the favored trajectory of the CAV, e.g. a lane-change. A *desired trajectory* is only provided in case the CAV detects the need to deviate from the current *planned trajectory* but external constraints (e.g. other traffic participants) hinder its realization.

A brief overview on the related work and concepts in the domain of *maneuver coordination* in the context of road traffic is provided in Section II. Our proposed generic approach for achieving maneuver coordination is presented in Section III. The research questions to be addressed in our future work are outlined in Section IV.

II. Related Work

As stated above, the overall objective of *cooperative driving* is to increase traffic efficiency, especially in the context of partially- and fully-automated vehicles. Consequently, the task required to reach this overall objective is to ensure appropriate coordination of individual objectives. As part of our literature review, we identified three modes of coordination: *longitudinal*, *lateral* and *right-of-way*.

Additionally, we identified two fundamentally different approaches for reaching coordination between traffic partic-

[1]Volkswagen AG, Group Research, 38440 Wolfsburg, Germany bernd.lehmann@volkswagen.de
[2]Volkswagen Group of America, Safety Affairs and Advanced Research, Auburn Hills, MI 48326, USA hendrik-joern.guenther@vw.com
[3]Institute of Operating Systems and Computer Networks, Technische Universität Braunscheig, 38106 Braunschweig, Germany wolf@ibr.cs.tu-bs.de

[1]Düring and Pascheka define cooperation in the context of vehicular traffic as voluntary behavior increasing overall utility for all involved vehicles [5].

978-1-7281-0322-8/18/$31.00 ©2018 IEEE

ipants. The first approach focuses on coordinating in very specific traffic scenarios only, whereas the second approach aims at establishing scenario-independent coordination.

The former approach has been widely researched and solutions are provided for a variety of use-cases: For C-ACC and truck platooning, only *longitudinal* coordination is required to maintain a minimal time gap to the preceding vehicle with the objective to improve the traffic flow [6] and to increase fuel efficiency [7]. The primary objective of these systems is to achieve *string stability*, which is required to avoid excessive speed oscillations for any string member [8–10]. String stability can be achieved by reducing the uncertainties associated with the maneuver prediction of string members. To reduce these uncertainties, additional control information are shared with all members of a vehicle string, using some sort of inter-vehicle communications.

For lane-changing and merging scenarios, both the *longitudinal* and *lateral* coordination modes apply: To enable lane-changing maneuvers, V2X communications is used to request and consequently increase the gap between two vehicles on an adjacent lane [11]. This is similar to merging scenarios, however the associated lane change needs to be completed before the lane closes, e.g. in case of lane reduction at on-ramps [12, 13]. In these scenarios, both modes of coordination apply, as one vehicle may have to slow down in order to increase the gap to a preceding vehicle, thereby enabling another vehicle to change lanes.

For all-way-stop intersections the *right-of-way* rule applies. Vehicles approaching this kind of intersection are expected to stop before entering the intersection. Right-of-way is given to the vehicle which first arrives at the intersection. To reduce the prediction uncertainty, it can commonly be observed that drivers will communicate with each other either by flashing lights or by gesturing. Research focuses on different approaches to decrease prediction uncertainties in these situations: on the one hand, distributed approaches focus on managing right-of-way by broadcasting a vehicle's intention prior to entering the intersection [14, 15]. On the other hand, centralized approaches such as Roadside Unit (RSU)-assisted cooperative intersection control with advanced scheduling concepts may govern right-of-way rules [16, 17].

However, focusing on solutions such as those presented above, means to cooperate in scenario-dependent approaches only. This may cause contradicting behavior in case several situations happen simultaneously and in close proximity.

Frese, Beyerer, and Zimmer present a scenario-independent concept which is based on forming groups of vehicles which have to interact as soon as a need for coordination is detected [18, 19]. Only vehicles which are part of a particular group may resolve a certain driving situation, regardless of the effect on adjacent groups. The concept does not include inter-group coordination, leading to inefficiencies at the group boundaries. Furthermore, each group identifies one group member as a central entity, calculating a specific maneuver for each group participant. However, a solution for the consensus mechanism for determining the central entity of the group is not presented. A communications protocol for distributing the individual maneuvers between all participants is also not proposed. Further questions related to the problem of deriving a path-planning algorithm capable of taking individual vehicle dynamics at the centralized planning instance into account are also not addressed.

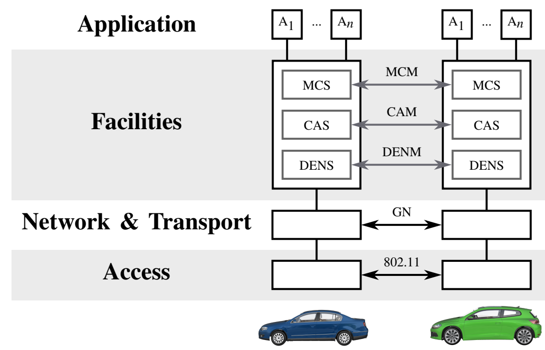

Fig. 1: Application-agnostic Maneuver Coordination Service

In general, we identified that regardless of the proposed concept, three distinct phases are required to reach coordination: A *detection phase* is responsible for identifying the need for coordination in the current driving situation. As part of a *negotiation phase*, coordinated behavior of traffic participants is achieved and eventually realized as part of an *execution phase*. However, most identified concepts leverage communications to resolve specific driving scenarios only. This results in a multitude of required communications protocols which are applicable to one scenario only. Consequently, every vehicle involved in the scenario has to be equipped with the same scenario-dependent application to provide the information required to reach coordination. On top of this, it has to be ensured that these protocols operate independently from each other.

III. A Generic Concept for Maneuver Coordination

In the following, we propose a generic concept to establish coordination between traffic participants. The concept is independent from a specific driving scenario and does not require every vehicle to be equipped with the same application. Section III-A introduces the technical foundation of our concept prior to providing details on the three phases of coordination from section III-B onwards. For reasons of simplicity, we first assume that all vehicles in the described scenarios are able to communicate and operate the same protocols. However, our proposed concept is also able to consider non-communicating vehicles.

A. Fundamentals

At the core of our concept stands the idea of realizing cooperation between traffic participants [5] by means of explicit communication. Taking the European Telecommunications Standards Institute (ETSI) Intelligent Transport System (ITS) G5 reference architecture [20] as a foundation, we introduce a new *Maneuver Coordination* service as part of the original *Facilities* layer, as shown in Figure 1. This service can be interpreted as a middleware for specific applications, such as the ones outlined in Section II. Each layer operates its own protocols which are used for the intra-layer communication. *Facility* layer services, for example, employ the well-known standardized Decentralized Environmental Notification (DEN) and periodic Cooperative Awareness (CA) message [3, 21]. Similarly, our proposed concept also provides a definition for a new sublayer protocol data unit, the so-called Maneuver Coordination Message (MCM). As depicted, this message aims at being agnostic to specific applications and focuses on exchanging trajectories, i.e. the spatial-temporal description of maneuvers. These exchanged trajectories are the result of application services $A_1, \ldots, A_n$ interacting with the maneuver coordination layer. Nevertheless, in case applications require additional information, application specific messages, e.g. for the management of a platoon [22] can be exchanged between the traffic participants as well.

As stated above, the basis for the maneuver coordination layer is the representation of trajectories in a standardized format independent from specific applications. For this purpose, the MCM contains trajectories represented in well-known *Frenét* frames [23, 24]. To compute the Cartesian representation $\vec{x}$ of a trajectory, the perpendicular offset d in the direction of a normal vector $\vec{n}_r$ at the root point $\vec{r}$ of a lane S is provided as:

$$\vec{x}(s(t),d(t)) = \vec{r}(s(t)) + d(t)\vec{n}_r(s(t)) \tag{1}$$

This frame allows the representation of vehicle movements in the spatial-temporal domain, using only a set of two polynomials: The covered arc length s of a given lane shape S at a specific point in time t is given by $s(t)$. The lateral offset d of the vehicle's reference point in the direction of the normal vector $\vec{n}_r$ at position $s(t)$ from the lane at a specific point in time t is provided by $d(t)$.

The methodology comes with the benefit of tolerance towards localization errors, as trajectories are described with respect to the current road layout only, e.g. on which lane out of a given number of lanes a trajectory starts. This enables vehicles to create a representation of their behavior regardless of its positioning accuracy, as only the current lane number needs to be detected. However, it is required that the geographic representation of the lanes, e.g. by means of a high-resolution map, is the same on all involved vehicles. This can be achieved by using the already standardized MAP message [25], as broadcast by infrastructure components, particularly at critical locations such as intersections.

The starting point of a trajectory is provided by the current position of the vehicle as a WGS84 coordinate. To be able to match the position of a vehicle to the corresponding lane on a map, additional information such as the orientation of its occupied lane as well as the total number of driving lanes of the current segment are provided by the disseminating vehicle.

The entire trajectory of a vehicle is expressed by concatenating multiple sets of $s(t)$ and $d(t)$ polynomials with exponent $k \in \mathbb{N}_0$, as depicted in Figure 2 and expressed in equations 2 and 3. A new set of polynomials is required for different segments, which are generated whenever a vehicle's trajectory intersects an adjacent lane (position β in Figure 2) or when the road topology changes (positions γ, δ in Figure 2). From the polynomial descriptions, the length of the segment can be inferred. The MCM also provides additional attributes for each segment, such as the available number of lanes as well as the connecting lanes of the next segment.

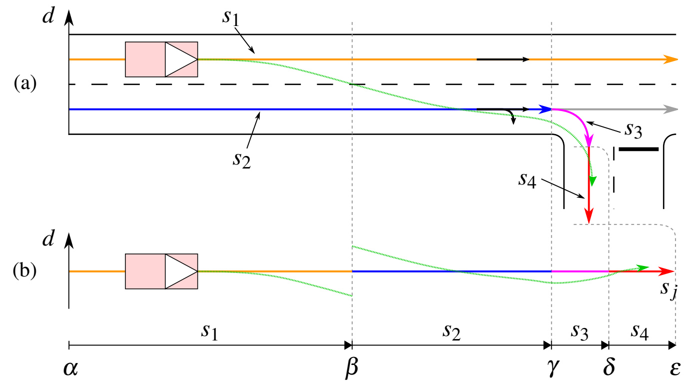

Fig. 2: Representation of a trajectory in a Frenét frame.

$$s(t) = \begin{cases} \sum_{k=0}^{n} a_k(t)^k & \text{for } t(\alpha) \leq t < t(\beta) \\ \sum_{k=0}^{n} b_k(t)^k & \text{for } t(\beta) \leq t < t(\gamma) \\ \sum_{k=0}^{n} c_k(t)^k & \text{for } t(\gamma) \leq t < t(\delta) \\ \sum_{k=0}^{n} d_k(t)^k & \text{for } t(\delta) \leq t < t(\varepsilon) \end{cases} \tag{2}$$

$$d(t) = \begin{cases} \sum_{k=0}^{n} e_k(t)^k & \text{for } t(\alpha) \leq t < t(\beta) \\ \sum_{k=0}^{n} f_k(t)^k & \text{for } t(\beta) \leq t < t(\gamma) \\ \sum_{k=0}^{n} g_k(t)^k & \text{for } t(\gamma) \leq t < t(\delta) \\ \sum_{k=0}^{n} h_k(t)^k & \text{for } t(\delta) \leq t < t(\varepsilon) \end{cases} \tag{3}$$

Figure 2 (a) depicts the required *Frenét frames* for a lane-change and turn at an intersection scenario. The position of a vehicle's reference point $\vec{x}$ along each lane is described using its lane-specific shapes (S_1, S_2). When the vehicle plans to change its lane (position β), a new set of polynomials is introduced. A new lane shape for the turning lane (S_3 at point γ) commences at the intersection. As the vehicle plans to turn onto S_3, a new set of polynomials is introduced[2]. Figure 2 (b) depicts the corresponding Cartesian representation when concatenating the provided Frénet frames. The velocity of the vehicle can be derived by differentiating $\vec{x}(s(t), d(t))$.

This representation stands at the core of our proposed methodology. The following sections detail how this concept is leveraged to provide a concept for maneuver coordination which is agnostic to a specific application.

B. Detection Phase

The first step towards reaching coordination in a specific scenario is to detect the actual need for coordination. Most

[2]Note: Even if the vehicle had decided to continue on S_2, a new polynomial would have been required as the road geometry changed.

of the scenario-specific approaches presented in Section II skip the detection phase as they target situations for which the need for coordination has been assessed off-line. Instead, these situation-dependent applications merely need to analyze whether the vehicle is currently in a situation where the application needs to be activated. Our proposed concept leverages the introduced Maneuver Coordination layer depicted in Figure 1 by providing means to detect the need for coordination regardless of a specific traffic scenario. The detection of a need for maneuver coordination is based on the following axiom:

Axiom 1. *Maneuver coordination between at least two involved communication-enabled vehicles is required in case at least one of these vehicles is hindered in the execution of an optimal maneuver due to another vehicle's planned maneuver.*

These maneuvers are encoded using the Frénet frames introduced in Section III-A. Whenever maneuvers intersect on the spatial-temporal domain (i.e. at least two vehicles would occupy the same space at the same time), a need for coordination prevails. We introduce a basic hierarchy between the maneuvers based on the right-of-way rules, as outlined in Axiom 2.

Axiom 2. *If planned maneuvers intersect on the spatial-temporal domain, right-of-way rules govern maneuver precedence.*

In the following, we call a vehicle which currently has the right-of-way an *accepting vehicle*. Vehicles which have to provide right-of-way are called *requesting vehicles*.

From Axiom 1, it follows that coordination can only be achieved for future maneuvers. Consequently, every vehicle needs to be able to compute its future behavior based on a predicted behavior of the surrounding traffic. This is in line with the behavior of human drivers planning their pursued trajectory based on assumptions on the behavior of surrounding traffic participants. For automated vehicles, these assumptions have to be trained and are subjected to the same prediction errors of human drivers. With the advent of V2X communications, automated systems are provided with the opportunity to reduce the prediction error by constantly broadcasting their planned behavior. The trajectories that vehicles are currently pursuing are called *planned trajectories* and represent a vehicle's future behavior. In case of planned trajectories intersecting on the spatial temporal domain, the *requesting* vehicle has to adapt its broadcast planned trajectory according to the right-of-way rules. This may happen in situations where the *requesting vehicle* transmits its *planned trajectory* prior to the *accepting vehicle*, e.g. in case of communication errors.

The coordinating aspect of our concept is introduced by a second trajectory that can be broadcast by a *requesting vehicle* in case an alternative, more optimal trajectory exists, which can, however, not be pursued due to conflicting right-of-way rules. We call this trajectory a *desired trajectory*. In order to derive a *desired trajectory*, vehicles need to be able to compare and assess trajectories. In our concept, this assessment is based on individual cost functions for each vehicle that can be applied to generated trajectories. In essence, these cost functions reflect the applications depicted in Figure 1, which evaluate the existence of a more optimal trajectory compared to the *planned trajectory*. If this is the case, the *requesting vehicle* will broadcast a *desired trajectory* along with the right-of-way observing *planned trajectory*, thereby indicating a need for coordination.

Figure 3a depicts an exemplary scenario in which vehicle A has detected the stopped vehicle B in front. Hence, vehicle A needs to change the lane in order to pass the stopped vehicle. Vehicle C broadcasts its planned trajectory, which intersects with a trajectory that would allow vehicle A to pass the stopped vehicle. As a result, there exists a need for coordination, as vehicle C's trajectory has right-of-way and vehicle A cannot change its planned trajectory to a more optimal trajectory immediately. Consequently, vehicle A starts broadcasting a *desired trajectory*, as depicted in Figure 3b.

C. Negotiation Phase

As stated above, in case a *requesting vehicle* has detected the need for coordination as the right-of-way rules hinder the execution of a preferable (e.g. more cost efficient) maneuver, it broadcasts a *desired trajectory* in addition to its *planned trajectory*. The presence of a *desired trajectory* can be interpreted as a detected need for maneuver coordination, as indicated in Figure 3b.

Any vehicle receiving the *desired trajectory* has to determine whether it is capable (and willing) to alter its current *planned trajectory* to enable the *requesting vehicle* to follow its *desired trajectory*. Every vehicle whose current *planned trajectory* intersects with the received *desired trajectory* is an *accepting vehicle*. Every *accepting vehicle* computes and evaluates a non-intersecting trajectory[3] with respect to the received *desired trajectory*. The *accepting vehicle's* evaluation is based on its own cost-function, taking parameters from the domain of driving comfort, time delay, etc. into account.

In the scenario depicted in Figure 3c, vehicle C is able to provide an updated non-intersecting *planned trajectory* by decelerating. Even if the updated trajectory of vehicle C would cause an intersection with another vehicle's planned trajectory (on the same lane), right-of-way rules need to be observed – thereby rendering the updated trajectory viable.

As a result of vehicle C accepting the received *desired trajectory* and by broadcasting an updated *planned trajectory*, the *requesting vehicle* is able to change its *desired trajectory* to become its *planned trajectory*, as depicted in Figure 3d.

If none of the receiving vehicles are able to account for the *desired trajectory*, the *requesting vehicle* withdraws its *desired trajectory* after a timeout. It should be noted that in order to provide an updated *planned trajectory*, a cascading process may be started, triggering an *accepting vehicle* to issue a *desired trajectory* itself.

[3]Depending on the traffic scenario, non-intersecting trajectories may not exist.

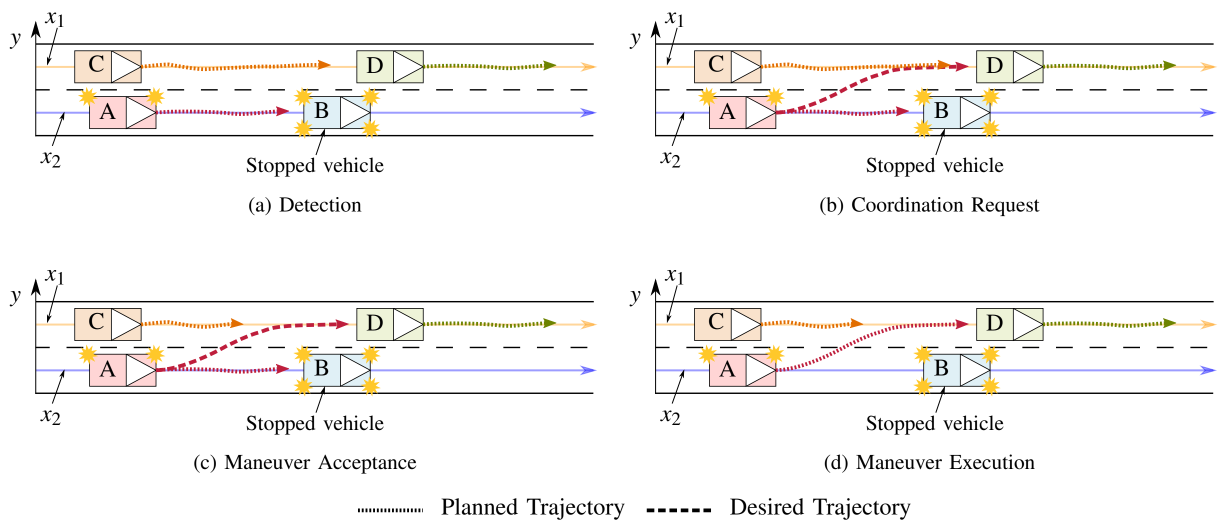

Fig. 3: Maneuver Coordination Process.

D. Execution Phase

The execution phase of our proposed maneuver coordination process (Figure 3d) is activated as soon as a *requesting vehicle* adopts its *desired trajectory* to become the *planned trajectory*. It is enabled to do so as a result of an *accepting vehicle* updating its *planned trajectory*. Throughout the execution phase, the vehicles keep updating their *planned trajectories*, based on the current driving scenario. Whilst the *requesting vehicle* follows its former *desired trajectory*, the *accepting vehicle* is required to follow its *planned trajectory* that has been updated when accepting the maneuver coordination request. The *accepting vehicle* still possesses the right-of-way and may therefore abort the maneuver, e.g. in case of unforeseen events. However, whilst following an enabled maneuver, the hierarchy of the vehicles imposed by right-of-way rules may change, e.g. as soon as a merging vehicle enters the target lane, it has right-of-way over the former *accepting vehicle*.

IV. Analysis and Challenges

The concept presented in Section III enables scenario-agnostic maneuver coordination between automated communicating vehicles by broadcasting trajectories. The need for coordination is detected based on intersecting received and internally planned trajectories.

The concept does not require all vehicles to be equipped with the same applications (e.g. CACC). Instead, the vehicles share the same application-agnostic protocol to exchange information about their planned behavior.

Several aspects need further analysis, mainly in the domains of potential corner cases, the design and implementation in automated vehicles, the communication between the traffic participants and the impact on traffic efficiency. The following sections provide an overview on the research questions that we are currently investigating.

A. Corner Cases

The proposed concept may lead to various situations or effects which need to be accounted for, when specifying the protocol:

a) Potential Ambiguities: Ambiguities may result when two intersecting *desired trajectories* are enabled to be adopted as *planned trajectories* as a result of a maneuver adaptation of an *accepting vehicle*, e.g. in case of two vehicles wanting to change onto the same lane. In these situations, the protocol has to provide means to resolve potential ambiguities at any detecting instance, for example by not enabling intersecting *desired trajectories*.

b) Cascading: Maneuver cascading results from situations where the realization of a *desired trajectory* depends on the realization of another *desired trajectory* of the *accepting vehicle* by a vehicle not related to the original maneuver of the *requesting vehicle*. Consequently, our analysis will address the effects of cascading on the protocol operations. However, boundary conditions may be formulated that annihilate the problem of cascading, regardless of the specific traffic scenario, e.g. by limiting the number of involved parties per maneuver.

c) Oscillation: Maneuver oscillations may result in cases where an already coordinated maneuver triggers yet another maneuver coordination at an adjacent party. However, as a result of the second coordinated maneuver, the original coordinated maneuver is rendered obsolete, hence causing an abortion of the latter.

B. Design and Implementation in CAVs

There are some practical challenges in the generation of *desired trajectories* introduced by our concept: Given a set of m feasible trajectories, a vehicle has to identify those trajectories leading to a potential collision by relying on received *planned trajectories* from surrounding vehicles. Any of those non-intersecting trajectories may then be chosen as the *planned trajectory* of the vehicle. The complexity associated with a collision check algorithm is in the order of $O(m)$, as every received *planned trajectory* has to be compared with every generated feasible trajectory for the host vehicle.

When computing the *desired trajectory*, the laws of basic vehicle dynamics have to be observed: the selection of the *desired trajectory* comes with an assessment of an existing feasible trajectory for the *accepting vehicle*, however from the perspective of a *requesting vehicle*. Hence, prior to transmitting a *desired trajectory*, the *requesting vehicle* has to assess the likelihood of an intersection-free *planned trajectory* for the *accepting vehicle*. With n vehicles in a scenario, including the host vehicle and m possible trajectories for each involved vehicle, the algorithmic complexity is in the order of $O(m^n)$. Every *desired trajectory* will be associated with an intersection to at least one *planned trajectory*. Given the algorithmic complexity and the dynamics of a driving scenario, further research will be required to meet the challenging time constraints for the trajectory assessment.

C. Inter-vehicle Communications

The backbone of our concept is to leverage inter-vehicle communications to continuously exchange both types of trajectories with nearby traffic participants. However, communications technologies like IEEE 802.11p share resources for communication between all communicating nodes. Consequently, we have to determine the communication requirements of the proposed concept.

Similar to the Cooperative Awareness Message (CAM), our protocol is based on a periodically transmitted message, the MCM. The necessity of coordination increases with traffic density - and with that the number of transmitted messages. This results in higher channel congestion and packet error rates. Missing packets, however, ultimately results in longer prediction times and the chances of missing disseminated *desired trajectories*, thus decreasing the effectiveness of the concept. To identify the communication requirements of our concept, we integrate our protocol in a microscopic traffic and network simulation environment, as outlined in Section IV-E.

D. Inter-dependencies

Whilst specifying our concept, we identified several inter-dependent research questions related to the aspects above:

a) Handling Prediction Errors: Although our concept reduces the uncertainties related to trajectory prediction, there are still several sources of prediction errors which need to be considered. In our explanation above, we assume that all traffic participants are able to communicate and as a result share their trajectories with each other. However, the maneuver coordination process also needs to account for non-communicating traffic participants by predicting their future behavior.

b) Message bursts: In case a high-priority MCM needs to be transmitted because of an urgent plan adaptation, surrounding traffic participants need to adapt their plans accordingly. An urgent plan adaptation may result in another traffic participant's need for an urgent adaptation as well, thereby causing a sequence of high priority messages. Hence, the employed communications technology needs to be capable of providing resources for message bursts without disadvantaging non-affected traffic participants.

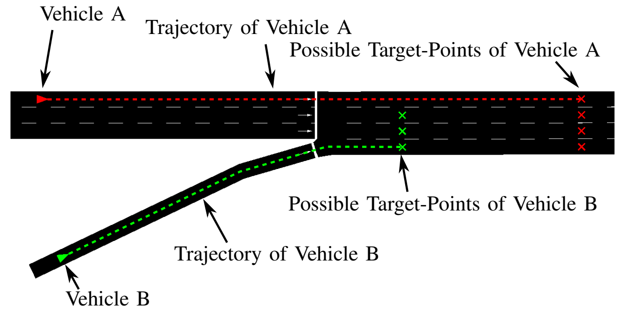

Fig. 4: Trajectories in SUMO

c) Traffic Efficiency: Broadcasting the planned behavior of traffic participants increases the predictability of local phenomena. Our concept accounts for the future behavior of the surrounding traffic, thereby increasing road utilization and traffic safety.

E. Simulation Environment

To analyze the research questions detailed above, we will employ *Artery* [26], an holistic simulation framework which couples the microscopic traffic simulator Simulation of Urban Mobility (SUMO) [27] and the dedicated network simulator OMNeT++ [28]. As part of our ongoing work, we extend *Artery*'s capabilities to also compute trajectories for individual vehicles. This allows for the analysis of both concept operations and communication-related research questions. Figure 4 depicts a simple merging scenario in SUMO, which is already utilizing the proposed concept. For each vehicle, a set of feasible end-points of trajectories for a certain time-horizon can be generated. Our ongoing research utilizes this simulation environment to derive further requirements and to specify the required data elements of the MCM.

V. Conclusions

The introduced concept for coordinating maneuvers represents a scenario- and application-agnostic mechanism to coordinate trajectories between communicating AVs. For this purpose, vehicles exchange their *planned* and *desired trajectories* as part of a standardized message format. The concept aims at reaching coordination between traffic participants by means of implicit confirmation. Explicit negotiation and confirmation of mutual trajectories is not required, as basic right-of-way rules govern the precedence of vehicle behaviors.

We also present a detailed summary of our ongoing research in the domain of maneuver coordination: aspects from different disciplines such as maneuver and trajectory generation, inter-vehicle communications and standardization have to be addressed.

ACKNOWLEDGMENT

This research was partially supported by the DFG Research Unit Controlling Concurrent Change, funding number FOR 1800.

REFERENCES

[1] C. Nath. “Autonomous Road Vehicles”. In: *POSTnotes No. 443* (Sept. 2013). `http://researchbriefings.parliament.uk/ResearchBriefing/Summary/POST-PN-443`.

[2] M. Buehler, K. Iagnemma, and S. Singh. *The 2005 DARPA Grand Challenge*. Springer-Verlag Berlin Heidelberg, 2007.

[3] *EN 302 637-2 V1.3.2 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*. ETSI, Nov. 2014.

[4] H.-J. Günther, R. Riebl, L. Wolf, and C. Facchi. “Collective Perception and Decentralized Congestion Control in Vehicular Ad-hoc Networks”. In: *2016 IEEE Vehicular Networking Conference (VNC)*. Dec. 2016.

[5] M. Düring and P. Pascheka. “Cooperative decentralized decision making for conflict resolution among autonomous agents”. In: *2014 IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA) Proceedings*. June 2014.

[6] B. van Arem, C. J. G. van Driel, and R. Visser. “The Impact of Cooperative Adaptive Cruise Control on Traffic-Flow Characteristics”. In: *IEEE Transactions on Intelligent Transportation Systems* 7.4 (Dec. 2006), pp. 429–436.

[7] A. Alam, A. Gattami, K. H. Johansson, and C. J. Tomlin. “Guaranteeing safety for heavy duty vehicle platooning: Safe set computations and experimental evaluations”. In: *Control Engineering Practice* 24.Supplement C (2014), pp. 33 –41.

[8] G. Naus, R. Vugts, J. Ploeg, M. van de Molengraft, and M. Steinbuch. “String-Stable CACC Design and Experimental Validation: A Frequency-Domain Approach”. In: *IEEE Transactions on Vehicular Technology* 59.9 (Nov. 2010), pp. 4268–4279.

[9] V. Milanés, S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura. “Cooperative Adaptive Cruise Control in Real Traffic Situations”. In: *IEEE Transactions on Intelligent Transportation Systems* 15.1 (Feb. 2014), pp. 296–305.

[10] K. C. Dey et al. “A Review of Communication, Driver Characteristics, and Controls Aspects of Cooperative Adaptive Cruise Control (CACC)”. In: *IEEE Transactions on Intelligent Transportation Systems* 17.2 (Feb. 2016), pp. 491–509.

[11] F. You, R. Zhang, G. Lie, H. Wang, H. Wen, and J. Xu. “Trajectory planning and tracking control for autonomous lane change maneuver based on the cooperative vehicle infrastructure system”. In: *Expert Systems with Applications* 42.14 (2015), pp. 5932 –5946.

[12] E. S. Kazerooni and J. Ploeg. “Interaction Protocols for Cooperative Merging and Lane Reduction Scenarios”. In: *2015 IEEE 18th International Conference on Intelligent Transportation Systems*. Sept. 2015, pp. 1964–1970.

[13] F. C. Chou, S. E. Shladover, and G. Bansal. “Coordinated merge control based on V2V communication”. In: *2016 IEEE Vehicular Networking Conference (VNC)*. Dec. 2016, pp. 1–8.

[14] S. Azimi, G. Bhatia, R. Rajkumar, and P. Mudalige. “Reliable Intersection Protocols Using Vehicular Networks”. In: *Proceedings of the ACM/IEEE 4th International Conference on Cyber-Physical Systems*. ICCPS ’13. New York, NY, USA: ACM, 2013, pp. 1–10.

[15] M. VanMiddlesworth, K. Dresner, and P. Stone. “Replacing the Stop Sign: Unmanaged Intersection Control for Autonomous Vehicles”. In: *Proceedings of the 7th International Joint Conference on Autonomous Agents and Multiagent Systems - Volume 3*. AAMAS ’08. Estoril, Portugal: International Foundation for Autonomous Agents and Multiagent Systems, 2008, pp. 1413–1416.

[16] J. Lee and B. Park. “Development and Evaluation of a Cooperative Vehicle Intersection Control Algorithm Under the Connected Vehicles Environment”. In: *IEEE Transactions on Intelligent Transportation Systems* 13.1 (Mar. 2012), pp. 81–90.

[17] K. Dresner and P. Stone. “Multiagent Traffic Management: An Improved Intersection Control Mechanism”. In: *Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems*. AAMAS ’05. The Netherlands: ACM, 2005, pp. 471–477.

[18] C. Frese, J. Beyerer, and P. Zimmer. “Cooperation of Cars and Formation of Cooperative Groups”. In: *2007 IEEE Intelligent Vehicles Symposium*. June 2007, pp. 227–232.

[19] C. Frese and J. Beyerer. “A comparison of motion planning algorithms for cooperative collision avoidance of multiple cognitive automobiles”. In: *2011 IEEE Intelligent Vehicles Symposium (IV)*. June 2011, pp. 1156–1162.

[20] *EN 302 665 V1.1.1 - Intelligent Transport Systems; Communications Architecture*. ETSI, Sept. 2010.

[21] *EN 302 637-3 V1.2.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service*. ETSI, Sept. 2014.

[22] M. Amoozadeh, H. Deng, C.-N. Chuah, H. M. Zhang, and D. Ghosal. “Platoon management with cooperative adaptive cruise control enabled by VANET”. In: *Vehicular Communications* 2.2 (2015), pp. 110 –123.

[23] M. Werling, J. Ziegler, S. Kammel, and S. Thrun. “Optimal trajectory generation for dynamic street scenarios in a Frenét Frame”. In: *2010 IEEE International Conference on Robotics and Automation*. May 2010, pp. 987–993.

[24] R. Toledo-Moreo, D. Betaille, and F. Peyret. “Lane-Level Integrity Provision for Navigation and Map Matching With GNSS, Dead Reckoning, and Enhanced Maps”. In: *IEEE Transactions on Intelligent Transportation Systems* 11.1 (Mar. 2010), pp. 100–112.

[25] *ISO TS 19091 - Intelligent transport systems - Cooperative ITS - Using V2I and I2V communications for applications related to signalized intersections*. ISO, Mar. 2017.

[26] R. Riebl, H. J. Günther, C. Facchi, and L. Wolf. “Artery: Extending Veins for VANET applications”. In: *2015 International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS)*. June 2015, pp. 450–456.

[27] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker. “Recent Development and Applications of SUMO - Simulation of Urban MObility”. In: *International Journal On Advances in Systems and Measurements* 5.3&4 (Dec. 2012), pp. 128–138.

[28] A. Varga and R. Hornig. “An overview of the OMNeT++ simulation environment”. In: *Simutools ’08: Proceedings of the 1st international conference on simulation tools and techniques for communications, networks and systems*. ICST, Belgium, 2008.