Cooperative Automated Driving Use Cases for 5G V2X Communication

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Abstract—Cooperative Automated Driving (CAD) brings together driving automation technology with vehicle-to-X (V2X) communication in order to enable vehicles to coordinate their driving maneuvers and achieve a common global knowledge of their surroundings, leading to safer and more efficient driving. The IMAGinE research project develops a CAD system based on collective perception and cooperative maneuver coordination and applies it to several use cases where CAD is expected to bring a significant benefit. Furthermore, a connected lane-merge function, recently demonstrated as proof-of-concept, shows a first step towards a safe and efficient cooperation among automated vehicles. 5G direct vehicle-to-vehicle communication may enable the implementation of CAD due to its enhanced communication performance.

Keywords—cooperative automated driving, V2X communication, 5G, collective perception, cooperative maneuver coordination, connected lane merge

I. INTRODUCTION

In the last few years, the capabilities of vehicles such as cars and trucks to drive with a certain level of automation are continuously improving, leading to a situation where the driver is increasingly responsible of supervising the vehicle control instead of actively steering it. These systems rely on real-time measurements by vehicle on-board sensors, such as radar, LIDAR or video cameras, which are integrated into a local environmental model (LEM) of the vehicle’s surrounding. A typical example is the combination of adaptive cruise control and lane keeping, which allows for automated highway driving with lateral and longitudinal vehicle control [1]. Also for inner-city scenarios automated driving systems are developing, see e.g. [2,3]. In general, the vehicle on-board sensors have a limited field of view and perception range, and especially single sensors do not work reliably in adverse weather conditions [4]. These limitations result in an inaccurate environmental model and potentially erroneous output of the vehicle controller.

Vehicle-to-Everything (V2X) communication enables nearby vehicles to behave cooperatively by exchanging information with each other, which allows overcoming the limitations of the vehicle sensors [5,6]. Currently there are two competing technologies to implement direct vehicle-to-vehicle communications [7]. The first one is based on the IEEE 802.11p standard, also known as DSRC in USA and ITS-G5 in Europe. It operates in the 5.9 GHz frequency band and it has been demonstrated on numerous field tests, it is therefore mature and ready to be deployed. The second technology is based on 3GPP cellular technology, known as C-V2X or 5G V2X and has emerged more recently as an alternative to enable direct communication among vehicles using the sidelink or PC5 interface [8]. The standard offers two operation modes, mode 3 or network-controlled mode and mode 4 or autonomous mode that is presented as an alternative to the 802.11p standard. A recent simulation-based comparison of 3GPP C-V2X and IEEE 802.11p for a platooning scenario finds that C-V2X delivers a higher communication reliability than 802.11p, while the C-V2X latency is higher but still fulfills the requirements of the platooning application [9].

Day-1 V2X applications (e.g., traffic jam warning) are based on the exchange of information among nearby vehicles and enable driver assistance systems which improve the driving safety, traffic efficiency and comfort. A basic such function is cooperative awareness, where vehicles broadcast data about their own state, such as their current position, speed and heading (in Fig. 1, the ego-vehicle detects vehicles 1 and 3 via cooperative awareness, but it cannot perceive non-V2X equipped vehicle 2). This service has been standardized worldwide, e.g. with the Cooperative Awareness Message (CAM) in Europe and by the Basic Safety Message (BSM) in the US. All V2X-equipped vehicles transmit these messages continuously with a variable frequency between 1 and 10 Hz, depending on the variation of their vehicle dynamic state (i.e., current heading, position and speed).

As a next step towards intelligent vehicles, cooperative automated driving (CAD) goes beyond by enabling vehicles not just to communicate, but also to interact with each other, influence other vehicles’ behavior and agree joint driving maneuvers, thereby enabling a higher level of automation. Recent experiments have shown that cooperative driving via V2X communication can improve the traffic efficiency by up to 42% over ego-centric driving [10]. The concept of CAD has been investigated in several European collaborative research projects, such as TransAID [11] and AutoNet2030 [12], and it is the focus of the German research project IMAGinE [13]. In this paper, we illustrate the IMAGinE approach on two key technologies to enable CAD: collective perception and cooperative maneuver coordination. Collective perception consists of the exchange of sensor data among nearby vehicles. This allows vehicles to include objects detected by other vehicles in their own environmental model, thereby increasing their awareness range, eliminating blind spots and improving the quality and reliability of individual measurements. Cooperative maneuver coordination allows vehicles to share their driving plans or intentions in order to find a common joint maneuver that benefits all traffic participants. This improves the vehicles ability to predict other vehicles’ future behavior and prevents misunderstandings among them, thereby avoiding possible conflicts or collision risks.

The remainder of this paper is organized as follows. Sec. II and III provide details on the developed concepts and the challenges found on collective perception and cooperative maneuver coordination, respectively, in the IMAGinE project. Sec. IV describes a number of use cases where cooperative...
driving is expected to bring a large functional benefit. Finally, Sec. V finishes with an outlook and future work.

Fig. 1 Vehicles 1 and 3 data concerning their own state in Cooperative Awareness Messages, while vehicle 1 also transmits vehicle 2’s data in Collective Perception Messages. The ego-vehicle can then perceive all other vehicles (also including non-V2X equipped vehicles). [14]

II. COLLECTIVE PERCEPTION

Collective perception [14, 15] allows cars to inform nearby vehicles of objects (e.g. pedestrians, objects or other vehicles) measured by their own on-board sensors (in Fig. 1, vehicle 1 detects vehicle 2 and transmits its data via collective perception). This enables receiving vehicles to extend their own environmental model beyond their own sensors range by looking through other vehicles’ “eyes”. The received object data by V2X communication are then incorporated into the vehicle’s environmental model, eventually combining the object data with that obtained from the on-board sensors by means of data fusion. This approach increases the redundancy of the detected object data, leading to a higher reliability.

This exchange of object data is done by means of Collective Perception Messages (CPM), currently in standardization by the ETSI [16] in order to ensure its interoperability among all equipped vehicles. The CPM format begins with an ITS Protocol Data Unit header (common to all standardized messages by ETSI), followed by three main data blocks. First, the station data container provides information about the sending station (vehicle or roadside unit), such as its current position and heading. Second, the sensor information container has details about the on-board sensors in the sending station, such as their number, range and aperture angles. Third, the perceived objects container is a list of the relevant objects detected by the sending station, including their relative position and speed, dimensions and other data.

Since the V2X frequency spectrum is scarce, the message generation rate and the number of included objects in the CPMs need to adapt dynamically to achieve a good trade-off between the improvement of the environmental model and channel load, thereby preventing channel congestion and a decreased V2X communication performance [15]. The CPM generation rules according to the current ETSI draft are based on the dynamic properties of the detected objects [16]. If the object dynamic state has changed in a way that would trigger the generation of a CAM by this object, it is then included in the next CPM. Highly dynamic objects are therefore more often included in transmitted CPMs as slow or static objects, leading to a higher CPM transmission frequency. The sensor information container is included in the CPM with a fixed frequency, similar to the CAM low frequency container.

The collective perception system in IMAGinE is illustrated in Fig. 2. Object measurements are received both from the vehicle on-board sensors and from V2X communications (CAM and CPM). The associated numbers reference the corresponding vehicles in the example from Fig. 1. The incoming measurements are associated to objects in the environmental model using the Hungarian algorithm. The data association is the most challenging part of the collective perception system. For instance, it requires to ensure the comparability of continuous (e.g. speed) and discrete (e.g. object type) features. Furthermore, the asynchronously and non-chronologically received measurements (due to the stochastic latency and the packet errors in the V2X channel) need to be synchronized to a common time instant, by means of prediction and/or retrodiction. A global time basis amongst all vehicles is therefore also required. For this purpose, the GPS time is used in IMAGinE.

The object data (e.g., position and speed) is then combined with its associated measurements by means of data fusion, thereby improving its accuracy. The data fusion framework consists of a Kalman filter together with a track management process, which creates a new object whenever a measurement cannot be associated to any existing object in the environmental model, or deletes an object whenever no corresponding measurements are received in a period of time.

Since the object data (e.g. its position) included in the CPM are often relative to the sender position, the CPM receiver needs to apply a coordinate transformation in order to store the object data in its environmental model relative to itself. Therefore, it is important that all involved vehicles have a precise positioning unit, requiring at least lane-level accuracy. Efficient and accurate algorithms for conversion between global and local transformation systems are also necessary. Furthermore, it is also key to ensure the comparability of the measured data from different sensor types (e.g. camera, radar, LIDAR) and manufacturers. This requires the definition of a common quality measure for all sensor measurements. Finally, a high-precision map is helpful to improve the localization accuracy of the ego-vehicle as well as of the objects in the environmental model (e.g. by assigning them to their current driving lane).

III. COOPERATIVE MANEUVER COORDINATION

In some complex driving situations, such as highway merging with dense traffic (see Fig. 3), a vehicle can benefit of cooperation with nearby vehicles. Cooperative maneuvers allow vehicles to express their cooperation needs and offer cooperation to other vehicles, leading to safer and more efficient joint maneuvers. Since cooperative maneuvers need to be agreed among several vehicles, they must speak a common language. An approach for maneuver coordination for automated vehicles based on the transmission of planned and desired trajectories has been recently proposed [17]. However, there exists to the best of our knowledge currently no standardized protocol for cooperative maneuvering.
Therefore, new maneuver coordination concepts have been developed within the IMAGiNE project. One of them, conceived by the authors together with Continental AG, is described in this section.

The maneuver coordination among vehicles can be realized following either a centralized or a distributed approach. In a centralized approach, such as proposed in TransAID [11], a central entity (typically a roadside unit) receives information about all involved vehicles via its own sensors and/or V2X communication and has therefore a global knowledge of the situation. It then plans a globally optimal and safe maneuver for all cooperative vehicles and communicates it via V2X. IMAGiNE, however, adopts a decentralized maneuver coordination, which does not require the presence of a roadside unit. In this case, the joint driving maneuver is obtained by solving a complex distributed organization problem, where vehicles exchange directly their maneuver intentions and needs via V2X communication, and adapt continuously their own maneuvers based on the reactions of nearby traffic participants.

Another way to differentiate cooperative maneuvering concepts is between explicit and implicit coordination. In an explicit approach, a dedicated cooperation process is started in an event-based manner once the need for cooperation is identified. For instance, the vehicle in need of cooperation transmits a cooperation request with a maneuver proposal, and other vehicles accept the proposal or send an alternative plan. This methodology requires that the coordination protocol considers all possible events (e.g., a vehicle does not follow its expected behavior) and adapts the cooperative maneuver accordingly. Furthermore, potential cooperation partners need to be explicitly identified and addressed. It becomes then increasingly complex when the number of cooperating vehicles and the variety of the cooperation scenarios increases. Due to these drawbacks, a generic approach for implicit maneuver coordination was developed in IMAGiNE. In order to remain independent of the use case and the driving situation, the cooperation protocol is based on the periodic transmission of trajectories with cost values via V2X communication. The trajectories represent possible driving paths for the ego-vehicle with a time horizon about 30 seconds in the future. The trajectory costs $C$ express how favorable the trajectory is for the ego-vehicle and they allow the relative prioritization of the transmitted trajectories. Three types of trajectories are considered:

- **Reference trajectory**: corresponds to the target trajectory being currently driven by the vehicle. Reference trajectories of all cooperating vehicles remain collision-free and potential collisions are solved according to the traffic rules. The reference trajectory cost indicates the extent of the ego-vehicle’s necessity for cooperation (when $C > 0$) or its willingness to cooperate with other vehicles (when $C < 0$). A cost $C = 0$ indicates that the vehicle neither is looking for cooperation, nor it is able to cooperate with other vehicles.

- **Alternative trajectory**: represents a cooperation offer from the ego-vehicle to another vehicle, i.e., a trajectory that the vehicle would be ready to drive in order to improve another vehicle’s situation. The cost of an alternative trajectory are by definition higher than the reference trajectory cost.

- **Requested trajectory**: expresses that the ego-vehicle has a need for cooperation from another vehicle in order to achieve its objective. Its cost is lower than the reference trajectory cost.

These trajectories are exchanged periodically among nearby vehicles via V2X communication in Maneuver Coordination Messages (MCM). An MCM format specified in IMAGiNE contains mainly three containers (see Table I for details). First, the message header includes basic message information, such as its generation time or the current vehicle automation state, which indicates whether the vehicle is currently driving in automated mode longitudinally, laterally, or both. The second container includes the vehicle current position in WGS84 format, including its lane in the case of a multi-lane road. Last, a trajectory list includes a reference trajectory, 0 to $N$ alternative trajectories and 0 to $M$ requested trajectories. In other words, the MCM always contains the vehicle current trajectory, optionally followed by at least one possible cooperation offer (alternative trajectory) or cooperation petition (requested trajectory) for other vehicles. All trajectories have a common format, consisting of a unique trajectory ID, a the path of the vehicle (position and heading) relative to its lane over time, information on road topology changes, the trajectory cost value, and an optional category to signalize special cases, such a high-priority trajectory sent by an emergency vehicle.

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<th>Table I. Format of Maneuver Coordination Message</th>
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<td>Header</td>
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<td>Current position</td>
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A drawback of this implicit maneuver coordination approach is that the trajectories included in the MCM must be correctly interpreted. Therefore, vehicles require a situation analysis algorithm that understands other vehicles’ intentions
based on their trajectories and the environmental model, which leads to an increased algorithmic complexity.

Fig. 4 Cooperative maneuver coordination in the highway merging use case. Vehicles transmit reference trajectories (violet), alternative trajectories (blue) and requested trajectories (green). The figures represent the respective trajectory costs.

Fig. 4 shows an example of a highway merging use case, where a truck driving on the highway proactively assists a car trying to merge in via cooperative maneuver coordination. The cooperation takes place in four steps:

(a) The truck A and car B transmit their reference trajectories (violet) with corresponding cost values -0.2 and 0.5. The truck identifies that the car is attempting to merge onto the highway and may require cooperation (due to the positive cost of the car’s reference trajectory). Therefore, it generates and transmits two alternative trajectories (blue).

(b) The car B receives the alternative trajectories from and notices that the truck A is willing to cooperate. Therefore, the car B calculates and transmits two requested trajectories, which are collision-free with the truck’s alternative trajectories. In this way, the probability of the truck accepting the cooperation request is incremented.

(c) The truck A selects the trajectory tuple (alternative trajectory from A + requested trajectory from B) which results in the lowest total cost and adapts its reference trajectory to match its selected alternative trajectory.

(d) Finally, the car B selects the corresponding requested trajectory as its reference trajectory and both vehicles drive their collision-free reference trajectories.

IV. COOPERATIVE DRIVING USE CASES

The concept for cooperative driving in IMAGinE has been designed to adapt to a multitude of use cases and driving scenarios. However, IMAGinE has selected several use cases where cooperative driving has a high expected benefit and could be implemented within a short time frame, in which to test and demonstrate the developed system. Besides the already mentioned cooperative merging use case, the following scenarios are considered (see Fig. 5) [13]:

- Cooperative longitudinal control on motorways: extension of Adaptive Cruise Control (ACC), by exchanging additional information among nearby vehicles as well as the traffic infrastructure. Vehicles synchronize their speeds according to the driving situation predictively and avoid unnecessary acceleration and braking, mitigating critical situations or even preventing them in advance.

- Cooperative overtaking on rural roads: vehicles exchange information about their own trajectory and speed and about objects in the environment as well so that drivers can be warned about oncoming traffic during overtaking maneuvers.

- Cooperative strategic traffic distribution: vehicles send information about traffic volume on main and side routes to a traffic center. The traffic center integrates data from vehicles and infrastructure and calculates an optimized traffic flow distribution before sending traffic distribution recommendations back to vehicles.

- Cooperative turning at junctions: transmitting turning intentions to other vehicles on the highway increases the vehicles’ signaling range and enables collectively coordinated turning maneuvers.

- Cooperative overtaking by heavy-goods vehicles: trucks find the optimal timing and coordinate their overtaking maneuvers on motorways by exchanging information about current and the planned target speeds in the near future and their current weight.

The exact communication requirements of these use cases is currently under research, but it is already clear that low-latency and highly reliable V2X communication will be key in all cases. This presents a challenge for current V2X technologies especially in dense traffic scenarios, such as a traffic jam on the motorway. Furthermore, an extended communication range would allow starting the cooperation process sooner, which is especially relevant in the cooperative turning use case. Therefore, 5G communication seems to be well suited to satisfy the requirements of cooperative automated driving.
A. Connected Lane Merge

An intermediate step towards the IMAGinE use cases is the Connected Lane Merge (CLM), which consists of a SAE level 3 automated lane change maneuver driven by the collective perception. The CLM function was developed as a proof-of-concept for cooperative driving and first showcased in a Bosch-internal demonstration in April 2019 at the test track of the Bosch research center in Renningen, Germany, shown in Fig. 6 (bottom).

The scenario setup is shown in Fig. 6 (top). The ego-vehicle (yellow) is equipped with a single front sensor, collective perception and automated maneuver control. Vehicle V1 (black) is also equipped with on-board sensors (radar/video) and collective perception. Vehicle V2 (blue) is a not V2X-equipped. The ego-vehicle is driving on the right lane of a highway and it detects that its lane is blocked by roadworks ahead, which it detects with its front camera or alternatively via a DENM V2X message from a roadside unit. Therefore, it needs to change to the left lane in order to cross the construction area. However, the lane change cannot be directly performed by its automated maneuver control, since the ego-vehicle’s single front sensor cannot perceive V1.

V1 is driving on the left lane of the highway and their on-board sensors measure the existing gap to V2, which is periodically transmitted via CPMs in order to support the lane change maneuver of the ego-vehicle. Depending on the size of distance between V1 and V2, the ego-vehicle can automatically calculate whether it can merge into the gap or has to slow down in order to change lane behind V1 or even to stop before the construction site. If the gap is large enough, the ego-vehicle performs a SAE level 3 automated lane change (Fig. 7, top). The development HMI (Fig. 7, bottom) shows a high-level representation of the vehicle environmental model, including a map of the test track and the detected objects by means of data fusion of input data from the ego-vehicle’s on-board sensors and received via V2X communication (CAM and CPM).

As a next step, extending the Connected Lane Merge function with maneuver coordination will enable use cases with a higher degree of cooperation, such as the cooperative merging on highways.
V. OUTLOOK

5G communication promises to enhance the capabilities of V2X communication in terms of latency, reliability and transmission range, thereby extending the role of V2X communication from driver assistance to enabling cooperative automated driving. Starting from a connected lane merge, where a vehicle performs an automated lane change thanks to collective perception, there are numerous use cases where cooperative driving can bring a significant benefit in terms of traffic safety and efficiency by enabling a higher degree of vehicle automation and maneuver optimization. The IMAGiNE research project explores some of these use cases and proposes novel concepts to implement collective perception and cooperative maneuver coordination following a generic and decentralized approach.

Future work includes investigating research questions such as quantifying the impact of the V2X communication performance in the functional benefit of cooperative driving in each use case, deriving the requirements for cooperative driving, such as the latency of V2X communication or vehicle positioning accuracy, and exploring the scalability of the cooperative functions as the number of involved vehicles and, consequently, the communication channel load, increases.

Fig. 7 Connected lane merge demonstration: view from the interior of the ego-vehicle (top) and detail view of the development HMI, displaying the vehicle environmental model (bottom).

REFERENCES


