An Extended Maneuver Coordination Protocol with Support for Urban Scenarios and Mixed Traffic

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Abstract—Coordinating the maneuvers between connected vehicles and other road users can increase traffic efficiency. To efficiently coordinate road users in a broad variety of maneuvers despite limited bandwidth, an appropriate message format and communication procedure must be defined. For this, first proposals have been made, mostly from a highway application perspective. However, we observe that many maneuvers that likely occur in urban scenarios are not covered by the existing proposals. Hence, in this work, we propose a new maneuver coordination message and a corresponding communication procedure with additional support for cooperative urban scenarios and mixed traffic of automated and manually driven vehicles. We illustrate the usage of our extended protocol with several example use cases.

I. INTRODUCTION

Coordinating the motion of connected vehicles and other road users offers a huge potential to further increase the traffic and fuel efficiency. However, to function on a large scale in real-world traffic across various platforms from different manufacturers, standardization is imperative. The European Telecommunications Standards Institute (ETSI) [1] standardizes messages and services for vehicle-to-anything (V2X) communication. The cooperative awareness message (CAM) [2] is a prominent result from this standardization. In turn, the standardization of a maneuver coordination scheme is still in its infancies [3]. Albeit first drafts have been proposed for the maneuver coordination message (MCM) [4]–[7], the existing proposals do not yet cover a sufficiently broad spectrum of application scenarios. Particularly, to the best of our knowledge, all the existing works do not consider centralized coordination schemes. The authors in [8] propose that one of the involved connected vehicles serves as a coordinator, in their scenario the vehicle closest to an intersection. However, in urban areas, edge computing resources can easily be provided, which can be used to efficiently coordinate cooperative road users.

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For connected and automated vehicles (CAV), a common approach is to send a *desired trajectory* in addition to their currently followed *planned trajectory* [5]. The desired trajectory is only feasible if other connected vehicles cooperate and accept the suggested maneuver or explicitly promise to follow a compatible trajectory [9]. In the survey [4], several decentralized approaches to cooperative driving are presented. With such approaches in mind, the ETSI started the standardization of the maneuver coordination service (MCS) and the corresponding MCM [3]. In the IMAGinE project, the message has been extended by a cost value representing how favorable the trajectories are for the sending vehicle [7]. The TransAID project [6] extended the MCM by a vehicle to infrastructure (V2I) interface, which assists in the negotiation of cooperative maneuvers. However, none of these proposals considered mixed traffic, i.e., automated and manually driven vehicles. The only MCM approach allowing for a centralized structure is [6], which only covers lane change maneuvers and speed advice. More complex scenarios, such as the coordination of junctions, are not considered.

In this paper, we extend the existing approaches and propose an MCM protocol with planning responsibility at a central coordinator. The coordinator can be a cooperating vehicle as proposed in [8], or a road side infrastructure server connected via ITS-G5 [1] or cellular network. We address mixed traffic with CAVs as well as connected non-automated vehicles (CV) with a human-machine interface (HMI). The coordinator can additionally receive and process CAMs and collective perception messages (CPM) [10] sent by connected vehicles and infrastructure sensors. By generating a merged environment model, the coordinator can even consider perceived non-connected road users. Our approach can benefit from edge computing, as a stationary edge server can provide more computational power than a road user. Due to the centralized structure, information processing and coordination of maneuvers is performed at a single entity. Thus, bandwidth and computational resources are saved. We extend the scope of other MCM proposals by supporting highway use cases and adding cooperative urban scenarios to provide a widely applicable protocol.

The rest of this paper is structured as follows: first, we describe the MCM extension in Section II. Then, the communication procedure is sketched in Section III. Finally, we discuss our proposed extension with example use cases in Section IV and finish with conclusions in Section V.

Maneuver-CoordinationMessage	ItsPduHeader			
	Maneuver-Coordination	GenerationDeltaTime		
		MCMParameters	BasicContainer (reference position, station type)	
			Maneuver-Container = CHOICE [...]	VehicleManeuverContainer (trajectory, route, advice response, ...)
			SuggestedManeuverContainer (ID, corridor, longitudinal waypoints, ...)	

VehicleManeuver-Container	VehicleState (type, speed, yaw angle)		
	Planned-Trajectory	StartDeltaTime, DeltaTime	
		List of TrajectoryPoint	XDistance, YDistance, Speed, YawAngle
	Desired-Route	List of Waypoint	XDistance, YDistance
Advice-Response	ManeuverID, AdviceUpdateID		
	AdviceFollowed (accept, reject, pending)		

SuggestedManeuverContainer	ManeuverID, AdviceUpdateID, TargetStationID				
	ParticipatingRoadUserIDs				
	ConfirmationRequiredFlag				
	ManeuverParameters = CHOICE [...]	SuggestedManeuver	List of Longitudinal-Maneuver-Waypoint	Waypoint (XDistance, YDistance)	
				MinArrivalTime, MaxArrivalTime	
				MinVelocity, MaxVelocity	
				MinDurationOfStop	
				PrecedingRoadUserID, FollowingRoadUserID	
				YieldToRoadUserIDs	
		Maneuver-Corridor	Polygon: list of (XDist., YDist.)		
TerminationStatus: regular maneuver end or error					

Fig. 1. Proposed *ManeuverCoordinationMessage* and the included *VehicleManeuverContainer* and *SuggestedManeuverContainer*. The *ItsPduHeader*, *GenerationDeltaTime* and *BasicContainer* are the same as in the CAM [2]. Optional entries are highlighted in gray.

II. PROPOSED EXTENSION OF THE MANEUVER COORDINATION MESSAGE

An overview of our proposed MCM is given in Fig. 1. Like in [6], our MCM also comprises an *ItsPduHeader* and a *ManeuverCoordination*, which consists of a *GenerationDeltaTime* and the *MCMParameters*. The *MCMParameters* are further subdivided into a *BasicContainer* and a *ManeuverContainer*. Following the definition of the cooperative awareness message (CAM) [2], the *BasicContainer* comprises the reference position and the station type of the transmitting agent. In contrast, the definition of the *ManeuverContainer* differs from [6]. To follow the one-service-one-message paradigm of the standard, the maneuver container is defined as a choice between a *VehicleManeuverContainer* or a *SuggestedManeuverContainer*, which is chosen according to the role of the communicating agent.

The *VehicleManeuverContainer* is transmitted frequently (e.g. with 1 – 10 Hz) by CVs and CAVs willing to participate in cooperative maneuvers. It includes the vehicle state, the planned trajectory, the desired route, and a response to a received maneuver suggestion. The *VehicleState* comprises the type (CV or CAV), speed and yaw angle of a vehicle. The position is already given in the *BasicContainer*. The optional *PlannedTrajectory* applicable to CAVs comprises a list of trajectory points, where each contains a speed and yaw angle in addition to a waypoint to avoid differentiation of roughly

discretized trajectories. The *DesiredRoute* contains a list of waypoints describing the route of the vehicle. The route has to be known to the coordinator but is mostly static, so it can be sent less frequently to reduce the average message size and thus is marked optional. The *AdviceResponse* refers to the *ManeuverID* and *AdviceUpdateID* of the suggested maneuver. It also contains the *AdviceFollowed* enumeration, which can take the states *accept*, *reject*, and *pending*, in case a vehicle has not yet confirmed or declined a request.

The *SuggestedManeuverContainer* is sent frequently (e.g. with 1 – 10 Hz) by the coordinator to connected road users participating in a maneuver to broadcast trajectory proposals, update parameters, and provide a watchdog functionality. The recipient is indicated through the *TargetStationID*, while the incremental *ManeuverID* and *AdviceUpdateID* serve as a reference for the vehicles sending their agreement or disagreement. The *ParticipatingRoadUserIDs* lists all road users involved in the maneuver and can be used, e.g., to show a selective environment model on the HMI screen. An advice response by the addressee is only necessary if the respective *ConfirmationRequiredFlag* is set to true.

A *SuggestedManeuver* consists of a list of *LongitudinalManeuverWaypoints* used to encode velocity constraints. Each entry has a *Waypoint* it refers to, an arrival time interval *MinArrivalTimestamp* and *MaxArrivalTimestamp*, and optionally a velocity interval *MinVelocity* and *MaxVelocity* that the vehicle is allowed to have at the respective waypoint. To include mixed traffic scenarios, the optional *MinDurationOfStop* is particularly helpful. For example, a bus driver may set a stop duration that the bus will certainly need for the passengers to disembark. Furthermore, the coordinator may add the IDs of the road users, *PrecedingRoadUserID* and *FollowingRoadUserID*, between which the addressed vehicle is intended to drive, to assist in gap synchronization. Additionally, a list *YieldToRoadUserIDs* is included, indicating the road users relevant to this longitudinal waypoint as described in Section III-D. Finally, an optional *ManeuverCorridor*, a list of coordinates, i.e. *XDistance* and *YDistance*, can be transmitted. It describes a polygon for the lateral constraints and is only applicable to connected automated vehicles. When a maneuver ends regularly or abnormally, a *TerminationStatus* is sent instead of a *SuggestedManeuver*.

The IDs in the *SuggestedManeuverContainer* referring to other road users are provided as additional information for a more efficient trajectory planning or a more comprehensive HMI display. Thus, the existence of a collective perception is not essential for the proposed MCM protocol. However, to efficiently use this information, the coordinator can additionally broadcast an environment model via CPM containing the road users that the respective IDs are referring to.

To avoid ambiguity, the coordinator needs to set the object IDs of perceived connected road users to their station IDs. The ETSI communications security architecture [11] proposes frequently changing station IDs to achieve pseudonymity. Therefore, if this is implemented, the Lock ID Change service in [11] has to be used to postpone station ID changes until the maneuver has been completed.

Fig. 2. Suggested MCM protocol.

III. COMMUNICATION PROCEDURE

An overview of the communication protocol is shown in Fig. 2a and explained in Sections III-A to III-C, with an example sequence diagram in Fig. 2b. A central coordinator has to be determined before maneuver coordination is possible. In case a road side infrastructure with a local server is available (known by a previously shared list of servers and corresponding governed regions), this edge server is handling the coordination. In autonomous scenarios without an edge server, a connected road user can initiate cooperative scenarios by serving as a coordinator, as described in [8].

A. Road user registration and maneuver preparation

Cooperative road users have to register at the coordinator to announce their presence and cooperation by regularly sending the *VehicleManeuverContainer* (stage 2a in Fig. 2). The frequency is chosen such that the expected errors remain tolerable. The planning module of the coordinator constantly analyzes the traffic scenario and determines if a cooperative maneuver could significantly improve traffic efficiency (stage 2b). As soon as such a maneuver is found, the respective corridors, trajectories, and intervals are planned and sent to the participating road users as described in Section III-C.

B. Maneuver execution as a road user

A road user participating in cooperative maneuvers receives *SuggestedManeuverContainers* with a maneuver advice (stage 3a in Fig. 2). In case of a CAV, the planning

module tries to plan a compatible trajectory and reports the result, whereas in a manually driven connected vehicle, the driver is asked for confirmation via the HMI. Until acceptance or rejection, a *pending* decision is sent to the coordinator. The lateral corridor and longitudinal intervals are chosen so that driving within those bounds is guaranteed to be safe, assuming typical physical bounds and adherence to accepted maneuvers of all road users.

After a road user accepted a suggestion (stage 4a), it executes the maneuver and can receive two types of maneuver updates. Updates with additional restrictions such as longer waiting times or lower velocities are marked by a flag and need another confirmation by the driver or planning module. Until confirmation, the decision is reset to a *pending* state. In turn, trivial updates with loosened constraints are automatically accepted without the need for confirmation. When no parameter is changed, the same maneuver with the *ConfirmationRequiredFlag* set to false is retransmitted.

C. Maneuver coordination

Most cooperative scenarios have a common structure (see Section IV): A different driving or crossing order than implied by the traffic rules is imposed on the participating vehicles. Some road users are prioritized, while others should yield to improve the overall traffic efficiency. Note that *yielding* is meant in a broader way and refers to slowing down or stopping to let other road users merge, cross, or pass. Therefore, a cooperative maneuver is considered to have a two-stage structure. To ensure safety, first, all yielding road users have to accept the suggested maneuver (stage 3b in Fig. 2). Afterwards, the prioritized road users are free to drive and can be given temporary right of way, encoded by the lateral corridor and longitudinal intervals (stage 4b). More complex dependencies between vehicles can be realized by additional negotiation stages. Until the end of the maneuver, regular parameter updates are sent to the participating road users to reflect a changed situation. To handle packet loss, a maneuver suggestion is re-transmitted until a response is received. A vehicle not responding for a certain time is assumed to reject the maneuver. When a suggestion is rejected or an accepted maneuver is violated at any time, the whole maneuver is aborted by the coordinator. In this case, the road users should fall back to regular driving and reach a traffic rule conform state as quickly as possible.

D. Preliminary constraint removal

Longitudinal constraints sent in a suggested maneuver are calculated with margins large enough to guarantee safety. Sometimes the constraining intervals are underapproximated. To retain traffic efficiency, a list of yield-to road user IDs can be sent, giving the road users relevant to the restriction. As soon as all included road users have become irrelevant (e.g., left the junction), the *LongitudinalManeuverWaypoint* can be disregarded and the yielding vehicle can drive on.

IV. USE CASES

To illustrate the broad applicability of our MCM extension proposal, the scenarios a) - e) shown in Fig. 3 are presented

Fig. 3. Example scenarios for the MCM usage. Green: coordinating vehicle or edge server; blue: connected vehicle; black: non-connected vehicle.

exemplarily. In all use cases, an edge server can be used for coordination. Some exemplary scenarios are shown where no edge server is available and the green vehicle serves as the coordinator. Sample messages were encoded in ASN.1 as proposed in [1]. The size of messages from the coordinator ranges from 57 B to 109 B in the shown use cases. Message sizes in the other direction depend on the trajectory and route granularity and reach 570 B for 60 trajectory points.

To show that our proposal handles existing cooperative use cases, the first scenario a) in Fig. 3 describes a Cooperative Adaptive Cruise Control (CACC) [12] situation, in which the leading CAV coordinates. The *DesiredRoute* indicates how long vehicles will stay in the platoon. The lateral corridor is not required, as it is given by the lane boundaries. Since CACC is mostly reactive, the *LongitudinalManeuverWaypoints* can contain only two elements. The *PrecedingRoadUserID* provides the predecessor of each CAV. The time and velocity intervals are broadcasted to all participants and allow for predictive CACC.

In scenario b), the coordination is performed by an edge server. The vehicle on the left lane needs to yield to ensure safety. The right vehicle is given a *ManeuverCorridor* polygon of seven waypoints describing the lane end and one *LongitudinalWaypoint* with a *MaxArrivalTime* and the left vehicle as a *FollowingRoadUserID*.

Scenario c) shows a lane change maneuver, where the coordinating vehicle requests the blue vehicle to slow down. For this, it sends one *LongitudinalWaypoint* and itself as the yield-to road user. After the blue vehicle accepts to yield, the green vehicle can safely change the lane.

In scenario d), for safe overtaking, the coordinating vehicle requests an oncoming CV to slow down. The overtaken CV could be a post van or dustcart that already frequently stops in urban scenarios. It is requested to stop at the curb with a *MinDurationOfStop*. The overtaking vehicle is given as the yield-to road user, so the stopping vehicle can already drive on if the overtaking is completed before the stop duration is over. Requesting a maximum velocity instead of a stop is an alternative to overtake slow vehicles, such as street cleaners.

Finally, scenario e) shows a junction in which the coordinator proposes the overall most favorable (e.g. energy efficient) maneuver, with one or two *LongitudinalWaypoints* and respective *YieldToRoadUserIDs* for each yielding vehicle.

V. CONCLUSION AND FUTURE WORK

In this paper, we presented an extension of existing MCM format proposals, adding urban scenarios to the use cases addressed in the cited previous works. The various scenarios are handled even in mixed traffic by coordinating connected automated and non-automated vehicles. Our extension additionally supports centralized structures, e.g., road side infrastructure with edge servers. We hope that our proposal can contribute to the ETSI MCM standardization efforts. In our ongoing work, we use the proposed MCM for edge server-based planning and coordination of connected road users to increase efficiency in cooperative urban scenarios. On a pilot site in real traffic [13], besides a proof-of-concept, we plan to evaluate also the communication protocol with respect to aspects like latency and reliability.

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