Preventing Failures of Cooperative Maneuvers Among Connected and Automated Vehicles

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ABSTRACT

Automated vehicles will be able to drive autonomously in various environments. An essential part of that is to predict other vehicles' intents and to coordinate maneuvers jointly. Such cooperative maneuvers have the ability to make driving safer and traffic more efficient. However, among the various communication protocols proposed for maneuver coordination, no single one satisfies all requirements. This paper assesses failure risks and mitigation strategies for cooperative maneuvers, including an analysis of popular protocols regarding this aspect. Next, we evaluate one particular cooperation protocol, the complex vehicular interactions protocol (CVIP), concerning performance of mitigation mechanisms and their influence on maneuver success rates or times to reach consensus among maneuver participants. Via simulation, we show that CVIP is suitable for cooperative maneuvers in realistic scenarios and investigate the trade-offs individual mitigation mechanisms face. These results are well-suited as guidelines and benchmark for other researchers developing cooperative maneuver protocols.

CCS CONCEPTS

• **Networks** → *Network performance analysis*; **Application layer protocols**; *Ad hoc networks*; • **Computing methodologies** → *Simulation evaluation.*

KEYWORDS

Connected vehicles; cooperative maneuvers; failure risk; performance evaluation; risk mitigation; vehicle-to-everything; V2X.

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MSWiM '21, November 22–26, 2021, Aliante, Spain.
© 2021 Association for Computing Machinery.
ACM ISBN 978-1-4503-9077-4/21/11…$15.00
https://doi.org/10.1145/3479239.3485721

ACM Reference Format:
Bernhard Häfner, Josef Jiru, Henning Schepker, Georg A. Schmitt, and Jörg Ott. 2021. Preventing Failures of Cooperative Maneuvers Among Connected and Automated Vehicles. In *Proceedings of the 24th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM '21), November 22–26, 2021, Aliante, Spain.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3479239.3485721

1 INTRODUCTION

Cooperation is essential for driving in today's traffic. As soon as a driver wants to perform any action they have to consider their surrounding environment and ensure their intents are understood. When changing a lane, they can use turning lights. On a four-way crossing without right-of-way signs, they may use eye contact and gestures to coordinate who goes first.

The equivalent is also true for automated vehicles. The combination of building intents, communicating them to others, and being understood correctly is vital for a smooth, efficient, and safe traffic environment. One way to achieve *cooperative maneuvers* among machines is via vehicle-to-everything (V2X) communication, which connects a vehicle with surrounding vehicles, traffic infrastructure, and other actors like cyclists or pedestrians. Vehicles can share intents over the air, process them, and agree on what to do next.

However, so far, no consensus has been reached on what protocol should be used to enable cooperative maneuvers and researchers currently investigate various approaches. Each has individual strengths and weaknesses, such as protocol complexity, induced network load, or clarity.

In a real-world scenario, not everything works out as planned. Therefore, it is crucial to investigate what obstacles are inherent to the protocols and what may go wrong during the negotiation and execution of cooperative maneuvers. Once researchers have identified these issues and ways to avoid them, they will become another dimension to compare proposals for cooperative protocols: how well particular protocols can mitigate failure risks and how they trade off risk mitigation for other design goals like efficiency and the range of enabled maneuvers.

This paper first analyzes such failure modes and compares three relevant cooperation protocols regarding their capability of risk mitigation. Next, we evaluate the effectiveness of our proposed mitigation strategies for the complex vehicular interactions protocol (CVIP), which we presented in previous work [7]. This study goes beyond the previous one in that it analyzes not only the communication aspects of CVIP, but also how well it enables actual maneuvers. Besides, the current paper performs an in-depth analysis of risks of failure and how CVIP mitigates them.

The main contributions of this paper are threefold: (1) evaluating different reasons for cooperative maneuvers' failures and comparing related mitigation strategies, (2) showing their effectiveness for one specific maneuver coordination protocol implementing some of these strategies, and (3) further evaluating this protocol regarding maneuver negotiation and execution.

2 RELATED WORK

Several protocol proposals for cooperative maneuvers exist. The basic element of *implicit* ones is the periodic transmission of intents, e.g., planned trajectories or models. Upon reception of intents, other traffic participants can infer whether they can adjust their own plans to accommodate others' desires. Lehmann *et al.* and related approaches [6, 11, 12] realize this via the periodic transmission of one's planned trajectory. Whenever a vehicle changes its plans, it additionally sends out a new desired trajectory. Other vehicles then evaluate intersections of their plans with this desire and may adjust their plans. Sharing own movement's model parameters [17], in contrast, lets vehicles more accurately predict driving behavior.

On the other hand, *explicit* protocols involve active acknowledgments or confirmations for maneuvers that an initiator plans. In the general space-time reservation procedure (STRP) by Heß *et al.* [9, 18], vehicles reserve road space, and others agree. Only if all necessary partners have confirmed will the initiating vehicle enter the reserved area. Application-specific approaches help to solve one specific traffic situation. For example, Hobert *et al.* [10] propose a protocol for lane changes involving an initiator sending a *lane change request* message, which another vehicle answers with a *lane change response*. The partner then opens a gap for the initiator and indicates completion with a *lane change prepared* message.

Some protocols also try to solve exceptional situations such as emergencies without communication. Manzinger *et al.* [16] use maneuver templates stored on each vehicle that can be compared to an encountered environment so that all present vehicles "intuitively" know what actions to perform to resolve the critical situation.

Our protocol CVIP [7] is a general, explicit handshake protocol. Its main advantages compared to other general, explicit protocols are that the initiator can propose actions also for all other participants and that counterproposals can be part of the negotiation. It involves the exchange of four messages during negotiation and execution. An initiating vehicle proposes cooperative maneuvers using the Cooperative Request Message (CQM) including an arbitrary number of maneuver containers specifying the cooperative actions for itself and potentially others. Receiving vehicles evaluate the proposal and accept or deny it via Cooperative Response Messages (CRMs). When receiving denials or proposed changes, the initiator can send an adjusted proposal for a new negotiation round. Once participants have reached a consensus, they initiate maneuver execution by transmitting the first Maneuver Status Message (MSM) and confirming it via Maneuver Feedback Messages (MFMs). Whenever subsequently the status for any individual action changes (e.g., from `planned` to `inProgress` to `finished`), a new MSM is sent and confirmed via MFMs, ensuring coordinated state transitions. In our previous work [7], we described cooperative maneuvers as comprising an *Awareness Phase*, a *Negotiation Phase*, and an *Execution Phase*. In this study, we concentrate on the latter two.

Sawade *et al.* [21] also investigated how to avoid maneuver failures. To this end, they prescribe roles to vehicles rather than concrete maneuvers and then let the vehicles themselves decide how to execute the assigned role. They do not elaborate on how participating vehicles may reassure themselves that others are still fulfilling the assigned role when in doubt, but they acknowledge that maneuver trajectories may be hard to adhere to strictly. In contrast to their work, this paper does not propose a new protocol but rather shows general challenges for all explicit cooperation protocols and what measures can alleviate these challenges.

3 BACKGROUND AND SYSTEM OVERVIEW

3.1 Background on Cooperative Maneuvers

In this paper, we evaluate the performance of our protocol CVIP in coordinating cooperative maneuvers. We define a *maneuver* as a temporally-ordered set of driving actions, where each action changes or continues the current mobility state of its actor for a specific duration. If more than one actor is involved, we call such a maneuver *cooperative*. This definition does not depend on any specific description of actions; they could be represented as trajectories, abstract maneuver names, or road-space reservations.

The system we are evaluating consists of connected and automated vehicles (CAVs) that drive on the road and want to perform a cooperative maneuver. We assume that no human-driven or non-connected vehicles take part in the negotiation. Once a vehicle determines the need for a cooperative maneuver, it will use vehicle-to-vehicle (V2V) communication to negotiate the maneuver with surrounding actors. This initiating vehicle is also called host vehicle (HV) or requesting vehicle, while the others are called remote vehicles (RVs) or responding vehicles.

For cooperative maneuvers, vehicles need to derive a shared understanding of which maneuver to perform jointly. What constitutes such a consensus primarily depends on the cooperative protocol used. Herein, we define it as the state when all vehicles know and agree on what to do. For implicit approaches [6, 11], after transmission of a desired trajectory that intersects at least one other vehicle's planned trajectory, a consensus is reached when all vehicles only send out planned, non-intersecting trajectories again. For Heß *et al.* [8], vehicles establish a consensus when after request transmission the confirmation is received, even though in their protocol, the HV only knows that RVs accept its own maneuver—a road space reservation— but not what actions they will take.

3.2 System Overview

For the simulations carried out in this paper, we run the software architecture depicted in Figure 1 on each vehicle. *Message Services*

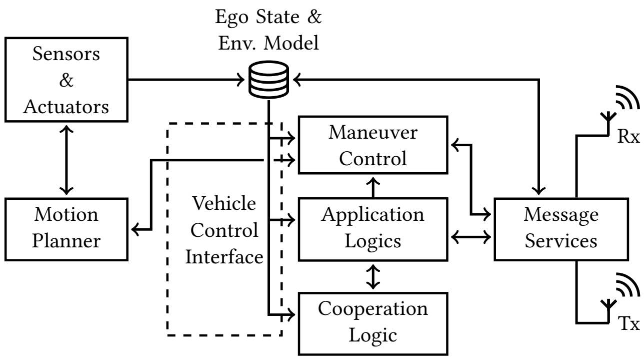

Figure 1: Software architecture deployed on each vehicle.

constantly run, prepare outgoing V2X messages, and forward incoming messages to the respective internal recipients. The *CAM Service*[1] updates the environment model of the vehicle according to the received Cooperative Awareness Messages (CAMs). It also periodically broadcasts CAMs including the current vehicle state (position, velocity, acceleration, etc.). The *Maneuver Service* processes messages related to CVIP. It forwards them to the *Application Logic*, which evaluates the current state and surroundings and decides whether or not to initiate a cooperative maneuver. This paper considers one specific application, a cooperative overtake, but in reality, different application logics may evaluate various cooperation possibilities. The subsequent *Cooperation Logic* decides on whether or not to execute a requested maneuver.

Once a vehicle decided to trigger a maneuver, the *Maneuver Control* takes over from the application logic. It is responsible for setting up all maneuver containers describing the cooperative maneuver and for keeping track of the execution states of the HV and all RVs. Therefore, the maneuver service forwards messages related to ongoing maneuvers to the maneuver control.

In order to deploy the framework on different targets and not be limited to a specific environment, the *Vehicle Control Interface* implements all functions needed for setting and retrieving ego state and environment values. Even real-world vehicles could replace the simulator by adjusting the interface and re-implementing the respective functions for getting and setting values. Additionally, the vehicle control interface is the primary interface for the maneuver control to trigger driving maneuvers by sending commands to the *Motion Planner*. This planner is the instance that usually calculates the vehicle's trajectory and controls *Sensors and Actuators*. If a maneuver is ongoing, then the vehicle control gives new short-term goals to the motion planner. In a real-world setting, the motion planner is itself a complex system enabling automated driving. If it detects a safety risk, it will still be able to cancel an ongoing maneuver for the sake of saving passengers' lives. The specific workings of the motion planner are outside the scope of this paper since we will focus our analysis on the maneuver control and the vehicle control interface and how well they enable driving maneuvers based on cooperative negotiation among CAVs.

[1]The CAM and maneuver services comprising the message services are not shown in Figure 1 to improve the clarity of the figure.

For CVIP, negotiating and agreeing on a cooperative maneuver is facilitated by CQMs and CRMs. The HV sends out a request containing a planned maneuver, and the RVs can respond. If all involved vehicles accept a proposal without changes, they have reached an agreement. The HV signalizes this by sending out an MSM with all maneuver statuses set to `planned`. The MFMs sent by the RVs function as a commitment to the planned maneuver. The execution will then start at the agreed time instant.

Going beyond our previous work [7], it is also possible to add dependent maneuver containers. These describe the start of an action not in absolute time elapsed from a reference time but relative to the start or end of another maneuver container. This allows for more flexible maneuver descriptions and ensures correct relative timing also in executions with deviations from the plan.

For our implementation, we choose abstract maneuver representations. The basic building blocks for maneuvers besides staying in current mobility state are thus: *accelerate* (positive or negative, can also be represented by a target velocity), *change lane* (left or right), *change heading angle* (including the amount of change in degrees or the curve radius), and *park* (direction and type of parking). These basic building blocks can describe all typical vehicular maneuvers like overtakes, merges, and intersection crossings.

4 CONSIDERATIONS ON MANEUVER FAILURES

Next, we investigate possible reasons for failures and measures to circumvent them, summarized in Table 1. This can work as a list of caveats for protocol developing researchers during their protocol design. We will refer to some of these failure modes in section 6.

With any explicit maneuver negotiation protocol, loss of the initial intent expression (CQM) implies a direct failure because surrounding vehicles will miss the HV's intent. Therefore, we introduced a retransmission mechanism based on a retransmission timeout (RTO). If no CRM is received after $t_{\text{rto}}^{\text{cqm}}$, then the CQM is resent. This can happen up to c^{cqm} times. Many implicit approaches rely on periodic transmission of intents, effectively mitigating the risk of not receiving an initial intent message.

All other messages in protocols with different message types can also get lost. In CVIP, we introduced retransmission mechanisms: for CRMs, the initiator will treat non-responding vehicles as uncooperative, designing a new maneuver without their participation. If a participant sent a CRM, but in the next CQM it is not included in the maneuver sequence, this indicates that the initiator did not receive its CRM. The vehicle will then retransmit its CRM to inform the initiator of the packet loss, enabling the HV to re-include the vehicle in a new proposal. The retransmission mechanism for MSMs is similar to the one for CQMs: if the sender did not receive any MFM after $t_{\text{rto}}^{\text{msm}}$, it resends the MSM up to c^{msm} times. If it receives some but not all MFMs it will also resend the MSM to tell the other maneuver participants that at least one vehicle's response did not arrive. We suggest that such retransmission mechanisms at the application layer should be implemented in every maneuver protocol not based on periodic transmissions since they prevent frequent maneuver failure for lossy communication channels. This retransmission is independent of lower-layer mechanisms increasing reliability, e.g., automatic repeat request.

Table 1: Failure modes and possible mitigation strategies

Failure mode	Sharing trajectories [11]	Space-time reservation [9]	CVIP [7]
Unresponding vehicles	Treat them as moving obstacles, replan own maneuver		
Deviations from agreed maneuvers	Judgement logic necessary; trade-off between precise descriptions and frequent deviations		
Miscalculations, reassessments, undetected vehicles	Improve sensor quality, sensor coverage, and maneuver planning algorithms		
Loss of initial intent	Periodic broadcast	Use retransmissions	
Loss of other messages	Periodic broadcast	Use retransmissions and define failure reactions	
Synchronization	Synchronized clocks		MSM-MFM transmission for state transition alignment
Uncooperative vehicles	Adjust desired trajectory, try again	Adjust road space intended for reservation, try again	Design new maneuver, if possible based on counterproposal
Emergency situations	Send updated planned trajectory, directly	Extend protocol to indicate emergency in reservation	Send request and then status, directly

Handling uncooperative vehicles is another issue. Vehicles may not send confirmations or deny proposed maneuvers. In the former case, the only solution seems to be treating them as uncooperative vehicles, i.e., obstacles. Several cooperative maneuver proposals take this approach [8, 16]. For the latter case, CVIP enables the RVs to send counterproposals. The HVs can consecutively send adjusted maneuver plans and mediate until the RVs are also willing to cooperate. With other protocols, it also may be beneficial to know whether other vehicles cannot negotiate, e.g., because they do not support the protocol or whether they do not agree to the current plan. Standards should thus prescribe that vehicles should respond to every received intent, even in case of denial. Furthermore, researchers should investigate how to set up rules on when receivers may decline a cooperation request and when not.

Miscalculations or unconnected, undetected vehicles pose another risk for failure to cooperative maneuvers. After agreeing to a supposedly safe maneuver, vehicles may, e.g., reassess the situation with new sensor data or detect unconnected vehicles in the maneuver area and now view the maneuver as unsafe. In such cases, the own passengers' safety will always take the highest priority, and the vehicle may thus cancel the maneuver. Depending on the actual driving situations, the vehicles may need to choose an emergency procedure to inform neighboring vehicles of immediate actions they intend to perform, e.g., as an evasive maneuver. For this kind of failure, the most effective proposal seems to be improving sensor quality and coverage such that the environmental model is as complete as can be before negotiating a maneuver. Approaches like collective perception, where vehicles share perceived objects, can help mitigate this issue. Besides, researchers should improve maneuver planning algorithms in order to reduce the risk of miscalculations. In our simulations, we assume all vehicles capable of V2X communication, so vehicles are aware of all surrounding vehicles even if individual CAMs may get lost.

The next aspect to consider is the synchronization of clocks or states. Especially if time dependencies between sub-maneuvers exist, every vehicle must know at all times the execution state of other participants. For this purpose, we designed the MSM-MFM transmissions. The MSM contains the sender's current view on execution states of every participant, incorporating the state change for its own maneuver that initiated the MSM transmission. If any other vehicle has a conflicting view, this will be clear from their transmitted MFM. The vehicle whose maneuver status is deviating may then send an MSM to update all participants on the actual status. When using the road-space reservation protocol [18], no state synchronization is necessary if only one resource per vehicle is reserved in one negotiation. As soon as more resources involving mutual dependencies are reserved, participants should track execution states. Depending on the driving situation, synchronized clocks may suffice so that every involved vehicle knows when to enter and leave certain road areas. Another possible approach is not formally to synchronize states but to use a dedicated logic component to infer ongoing maneuver execution from received CAMs of other vehicles. While this reduces the risk of failure due to unsuccessful state synchronization, it is currently unclear how to design a deterministic "judgment logic" evaluating what action another participant is performing. Such a state synchronization mechanism may be unnecessary for protocols involving periodic transmissions as long as messages are reliably received.

Related to this is the question of how to handle deviations to planned maneuvers during the execution phase. In cooperative maneuvers, all traffic participants need to rely on each other. However, the vehicles' driven maneuvers may deviate from the planned ones, e.g., the vehicle may drive slower than intended due to slopes or sensor inaccuracies. It is thus crucial to check whether the deviating vehicle still participates. This is independent of whether or not participants exchange messages during the execution phase. In CVIP, a "doubting vehicle" can send an MSM and wait for the "deviating" vehicle's response. If the reported status aligns with the assumption, then the doubts may be dispelled. In CVIP there is also the possibility of providing a parameter range, e.g., a target velocity corridor, to mitigate this issue partly. When using other protocols, vehicles similarly have to assess deviations from agreed maneuvers. Balaghiasefi *et al.* [5] present first ideas on deviation detection. Approaches like the one from Sawade *et al.* [21] may lead to less frequent deviations but have to compromise on the exactness of maneuver descriptions to reach this goal.

Finally, situations may happen where time is not sufficient to reach a consensus via negotiation, requiring immediate (re)actions. For such emergencies, vehicles may need to execute a maneuver directly and should at least use special procedures to inform others about the action they are about to perform. With trajectory broadcasts, a vehicle may, for example, change its planned trajectory directly. For the STRP, Heß *et al.* [9] did not mention an emergency procedure. We envision two mitigation strategies: extending the protocol to include an emergency flag or similar in the reservation, or adjusting the transmission mode during emergencies, e.g., quickly retransmitting the reservation to indicate that the HV has to enter the mentioned road area. In CVIP, those two approaches could work as well. In addition, it is possible to send, and potentially retransmit, a CQM directly followed by an MSM, both containing only maneuvers for the HV. Like this, surrounding vehicles will become aware of the immediate subsequent actions of the HV. These mechanisms allow at least intent-sharing in situations where negotiation and agreement-seeking are not possible.

5 SIMULATION SETUP AND ASSUMPTIONS

For evaluating our protocol and mitigation measures, we set up a simulation framework combining the network simulator ns-3 [4], the traffic simulator SUMO [13], and the intelligent transport system (ITS) framework ezCar2X [3] that enables connected applications [20]. As an evolution from our previous work [7], the application logic can now directly trigger driving maneuvers that simulated vehicles then carry out.

While it is impossible to model reality in every detail, simulations help understand the employed mechanisms' effectiveness. Besides, control over boundary conditions and actor behavior is usually better and more accessible in simulation than in real-world experiments. For the experiments within our study, especially the ability to induce artificial packet losses and accurately perform maneuvers as planned are relevant. The investigation of the mechanisms in real-world deployments is left for future research.

We model the simulation of the sensors and actuators as well as the "uncooperative motion planner" (left side of Figure 1) within SUMO. The vehicle control is implemented via SUMO's TraCI interface and connects SUMO with the ezCar2X modules for maneuver control and application logic. Those can also access the ego vehicle's state and the current environment model as received by CAMs using the TraCI interface. The message services are part of the ezCar2X framework implementation, too. For the actual transmission and reception of all involved messages, we use the ns-3 simulator. The maneuver control performs the housekeeping of execution states within the current cooperative maneuver.

For our evaluation, we analyze the basic use case of a *cooperative overtake*, see Figure 2. The HV, driving 20 m/s, approaches an RV driving 10 m/s. All vehicles exchange periodic CAMs and are thus aware of all surrounding vehicles. Based on the distance to the RV,

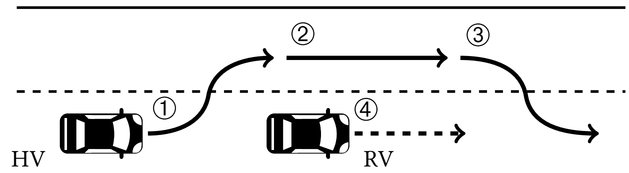

Figure 2: Use case illustration of a cooperative overtake: the host vehicle initiates it and involves the remote vehicle. The encircled numbers are referenced in the text.

Table 2: Simulation parameter ranges

Parameter	Values	Parameter	Values
Simulated time	30 000 s	p_{drop}	0 to 0.5
$t_{\text{rto}}^{\text{cqm}} = t_{\text{rto}}^{\text{msm}}$	{20, 50, 100}ms	$c^{\text{cqm}} = c^{\text{msm}}$	0 to 4

the velocity difference, lane matching, and a check whether fast vehicles are approaching from behind, the application logic of the HV triggers an overtake maneuver including all relevant vehicles. CVIP enables the maneuver control to flexibly design a cooperative maneuver, including both HV and RV actions. The HV will thus send a cooperative maneuver including the three sub-maneuvers *change lane* ①, *accelerate* ②, and *change lane* ③ for itself and the maneuver *keep current mobility state* ④ for the RV. The RV then evaluates this proposal. Its cooperation logic checks for collisions and, in this paper, agrees to the overtake if it detects none.

Since designing optimal cooperative maneuvers is beyond the scope of this paper, our overtake proposal is static: we manually assign all maneuver containers' durations to fixed values (5 s for each lane change and the HV's overtake, and 15 s for the RV's straight movement with constant velocity). A more sophisticated maneuver control should specify a cooperative maneuver based on relative velocities, distances, and other surrounding vehicles.

In our simulation, we also neglected safety of the intended functionality (SOTIF) [2] checks by which actors would judge maneuvers' safety. Automated vehicles should only propose maneuvers that will not lead to a collision or other risk for passengers and constantly check safe execution as part of their safety concept. Such an analysis is outside the scope of this study, but approaches for safe maneuvers exist in the literature [15].

Our simulations are performed on an oval test track involving one HV and four RVs. The advantage of an oval test track is that the circular road allows for long simulation times involving several cooperative maneuvers. We chose an oval track to also have stretches of straight roads where overtakes are possible more easily. The parameter ranges used, cf. Table 2, allow for 400 to 420 successful overtake maneuvers under low packet loss rate (PLR) conditions. For higher PLRs, the total number of proposed maneuvers increases since the HV often triggers a new overtake in case a previous attempt failed. We vary $t_{\text{rto}}^{\text{msm}}$ in the same steps as $t_{\text{rto}}^{\text{cqm}}$, but as expected, this variation only minimally affects execution times, which are mainly determined by submaneuvers' execution duration (i.e., several seconds). For the evaluation of maneuver success rates, we induce packet losses drawn from a Bernoulli distribution with the respective target PLR p_{drop}. Propagation effects like fading slightly add to the overall PLR.

6 EVALUATION

Researchers have not yet systematically investigated how to evaluate cooperative maneuver negotiation protocols. Existing studies either comprise no evaluation at all [10–12] or apply different metrics like channel busy ratio (CBR) of the Wifi-based ITS-G5 communication [6] or the time from request transmission to commit reception during test drives [8]. This heterogeneity hinders direct comparison to other protocols' performance, but we refer to existing research findings where appropriate, below.

This study evaluates how well CVIP performs in enabling cooperative maneuvers, and how the mitigation mechanisms from section 4 improve performance. Thus, we varied specific protocol parameters to deliver good results for cooperative maneuver coordination. Our evaluations, especially those regarding mitigation mechanisms, apply beyond CVIP to many other approaches for maneuver coordination. Therefore, we will concentrate our evaluation on metrics of general interest with maneuver negotiation and execution without making protocol-specific assumptions.

Our first metric is the *time to reach consensus* or *negotiation time* after the transmission of intents. In CVIP, this is the duration from transmission of the first CQM until the first MSM is sent.

The negotiation time for no retransmissions, i.e., $c^{\mathrm{cqm}} = 0$, is—depending on the used technology, number and distance of involved vehicles, and channel load—in the single-digit range of milliseconds, since our cooperation logic only checks proposals for collisions. As soon as CQMs can be resent to "save maneuvers from failing," negotiation time increases. Figure 3 demonstrates this for $t_{\mathrm{rto}}^{\mathrm{cqm}} = 20$ ms, Figure 4 for $t_{\mathrm{rto}}^{\mathrm{cqm}} = 50$ ms, and Figure 5 uses $t_{\mathrm{rto}}^{\mathrm{cqm}} = 100$ ms. Together, these three figures show that the average negotiation time for a specific PLR and c^{cqm} increases approximately proportional with $t_{\mathrm{rto}}^{\mathrm{cqm}}$. In future systems, $t_{\mathrm{rto}}^{\mathrm{cqm}}$ should depend on the expected time for processing of cooperation willingness: within $t_{\mathrm{rto}}^{\mathrm{cqm}}$, the cooperation logic needs to receive and evaluate the proposal, and the respective CRMs should arrive at the HV. In our simulations, checking for collisions took a maximum of 2 ms and usually stayed well below this limit. Heß *et al.* [8] state that for their STRP, the time necessary to analyze a request and respond to it was on average 0.47 s, although they do not specify which feasibility checks they perform within this time. Nichting *et al.* [19] extend their work and state that for the two-vehicle case of reservations at an intersection crossing, the mean time from sending a request to reception of a response was 155 ms, with a standard deviation of 33 ms. This comparison suggests that CVIP's efficiency is comparable or superior to at least one other explicit approach.

Considering typical driving situations, negotiation times below 1 s should be acceptable since, for the low relative velocities involved, in such time periods the situation will not change much and the negotiated maneuver remains valid. Even in extreme cases of relative velocities $v_{\mathrm{rel}} = 300$ km/h—for the rare case of vehicles driving in opposite directions with 150 km/h each— under the conservative assumption of 300 m communication range for V2X direct communication technologies, the total time budget to collision is

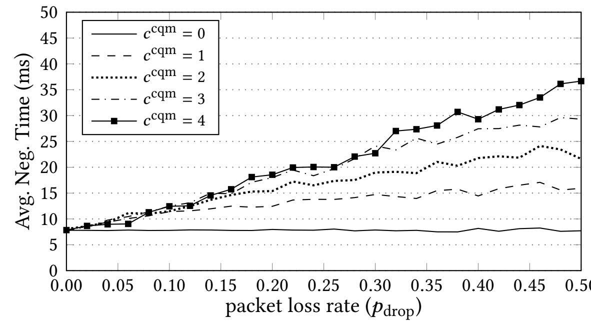

Figure 3: Time to reach consensus (from first CQM to first MSM) vs. p_{drop}, for different retransmission counters c^{cqm} and retransmission timeouts $t_{\mathrm{rto}}^{\mathrm{cqm}} = 20$ ms.

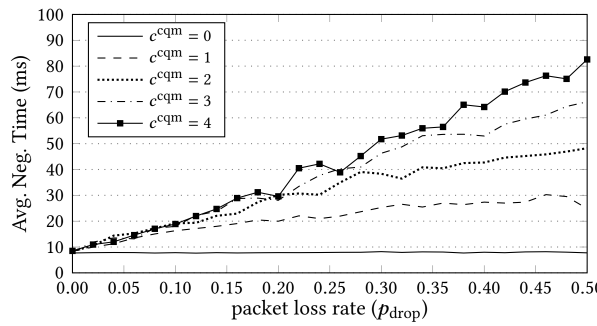

Figure 4: Time to reach consensus vs. p_{drop}, for $t_{\mathrm{rto}}^{\mathrm{cqm}} = 50$ ms.

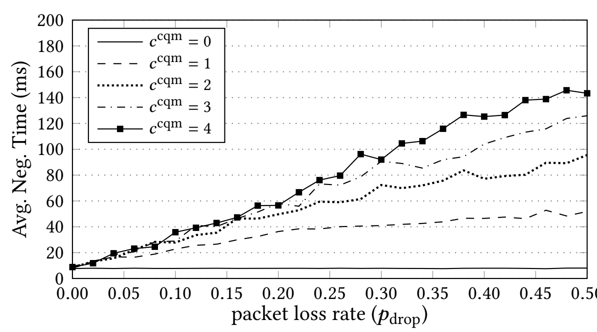

Figure 5: Time to reach consensus vs. p_{drop}, for $t_{\mathrm{rto}}^{\mathrm{cqm}} = 100$ ms.

$t_{\mathrm{ttc}} = \frac{300\,\mathrm{m}}{300\,\mathrm{km\,h^{-1}}} = 3.6$ s. For special cases with high relative velocities, e.g., $v_{\mathrm{rel}} > 200$ km/h, small $t_{\mathrm{rto}}^{\mathrm{cqm}}$ are generally beneficial to finish negotiations quickly. As an example, with $t_{\mathrm{rto}}^{\mathrm{cqm}} = 100$ ms, relative distances have already changed by 5.5 m.

The maximum negotiation time is approximately bounded by $c^{\mathrm{cqm}} \cdot t_{\mathrm{rto}}^{\mathrm{cqm}}$. These two parameters thus have to be chosen such that this bound does not exceed the target time window, e.g., 1 s. One feasible parameter combination seems to be $t_{\mathrm{rto}}^{\mathrm{cqm}} = 50$ ms, $c^{\mathrm{cqm}} = 4$. Here, the retransmissions mitigate many maneuver failures otherwise occurring. Still, the average negotiation time will stay below

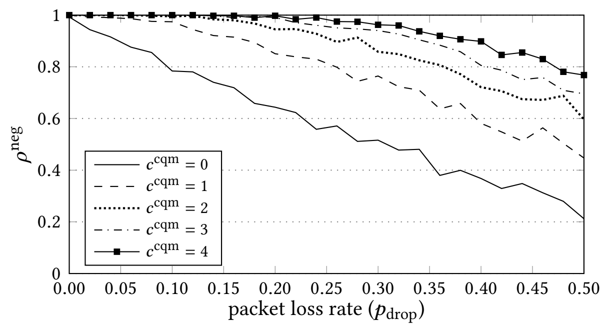

Figure 6: Ratio of successful maneuver negotiations ρ^{neg} vs. p_{drop}, for $t_{\text{rto}}^{\text{cqm}} = 20\,\text{ms}$.

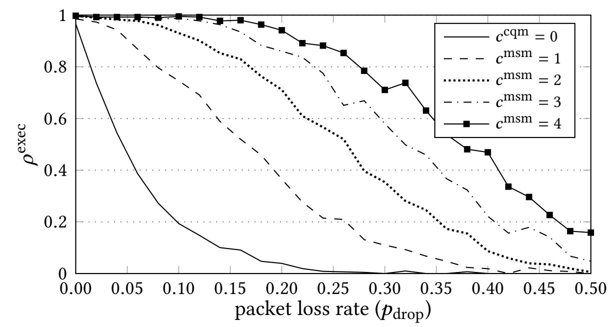

Figure 7: Ratio of successful maneuver executions ρ^{exec} vs. p_{drop}, for $t_{\text{rto}}^{\text{cqm}} = 20\,\text{ms}$.

100 ms, such that driving situations will not change much, and renegotiations are possible if necessary. On the other hand, if cooperation logics will get more sophisticated and take up more than 50 ms, the value for $t_{\text{rto}}^{\text{cqm}}$ may need to be recalibrated and a higher value may become more feasible. This directly creates a trade-off between flexibility, i.e., renegotiations, and calculation complexity, i.e., cooperation and application logics. The more complex the calculations, the more time they need. However, the longer it takes to send feedback and negotiate a maneuver, the more likely substantive changes to the surrounding traffic situation become.

Besides investigating this timing-related behavior, we are interested in the success rates ρ of our protocol facing packet losses. Since the results are similar for all sufficiently large $t_{\text{rto}}^{\text{cqm}}$, i.e., longer than the processing time, we only include graphs for $t_{\text{rto}}^{\text{cqm}} = 20\,\text{ms}$. Going beyond [7], we now distinguish between successful maneuver negotiation, shown in Figure 6, and maneuver execution, shown in Figure 7. As can be seen, retransmissions are an effective measure to mitigate negotiation failures, reaching[2] $\rho^{\text{neg}} > 0.9$ even for $p_{\text{drop}} > 0.3$, using $c^{\text{cqm}} \geq 3$.

Even for high PLRs, vehicles can negotiate maneuvers successfully—potentially after one or two retries. The assumption that the conditions that triggered the maneuver are still present should hold for most failed negotiations in case of small $t_{\text{rto}}^{\text{cqm}}$.

Successful executions are more challenging. Using up to four retransmissions yields $\rho^{\text{exec}} > 0.95$ up to $p_{\text{drop}} = 0.18$, but around $p_{\text{drop}} \approx 0.24$, ρ^{exec} drops below 0.90. Mansouri *et al.* [14] conclude based on simulations that vehicular LTE (LTE-V) will yield PLRs below 0.3 for transmission distances of 300 m. Such values indicate that CVIP is also feasible for the execution phase.

Investigating the maneuver execution failures in more detail, we discovered that most maneuvers fail before even one sub-maneuver is finished, see Figure 8. For $p_{\text{drop}} \leq 0.12$, the figure is distorted because only a few maneuvers (≤ 2) fail out of all runs with the same parameter setting. For p_{drop} from 0.14 to 0.22, slightly less than half of the maneuvers failing do so during the beginning of the cooperative maneuver. The ratio of maneuvers not even reaching beyond the first lane change, which is the first maneuver container, increases with PLR as expected. We only show the results for $c^{\text{cqm}} = 2$, but the graphs look similar for other retransmission limits. Especially the ratio of ≈ 0.4 of maneuvers failing before the first lane change in case of low PLR is comparable throughout all simulated parameter sets. Only what "low" means depends on c^{cqm}: without retransmissions $> 50\,\%$ of maneuvers fail without finishing one maneuver container even for $p_{\text{drop}} = 0.02$. For $c^{\text{cqm}} = 4$, more than one maneuver out of 400 fails only starting at $p_{\text{drop}} = 0.22$ (graphs not shown due to space limitations). This finding has implications for safety since most maneuver coordinations will fail when the HV has not even finished changing lanes. In this situation, the initiating vehicle can easily adapt to maneuver failure by directly changing back to the original lane. Later, when the HV is closer to the RV it overtakes, adaptions would be more dangerous.

7 DISCUSSION AND FUTURE RESEARCH

Our results show that CVIP constitutes a flexible, robust way for maneuver negotiations. Especially retransmissions mitigate the lossy nature of the wireless transmission channel effectively. Still, they trade off reliability with the time to reach consensus. Future studies should investigate acceptable time margins and failure rates, e.g., for negotiating cooperative maneuvers.

It is also necessary to investigate the magnitude of channel losses in real-world driving scenarios and their influence on protocol performance. If channels are too lossy, protocols may need to employ other mitigation mechanisms than retransmissions: judgment solely based on received CAMs, or periodic transmission of a "participation beacon," for example, as an extension of the CAM. In the end, such alternative mechanisms will need more complex decision logic for maneuver cancellation. However, depending on real-world channel conditions, they may yield higher maneuver success rates as participants will not cancel maneuvers based on missed messages during the execution phase.

To prepare for real-life deployments, researchers must also investigate more complex maneuvers. A limitation of this study and many others [8, 11, 18] is the focus on a simple scenario like a cooperative lane change (CLC) or overtake. If cooperative maneuvers are to become a reality on our roads, they should perform well also with many vehicles present or participating and for more complex maneuvers. Different levels of maneuver complexity seem achievable with different protocols, but at present, no categorization of cooperative maneuver "complexity classes" exist.

[2] As no agreed value for "good performance" of a cooperative maneuver protocol exists, we use 0.9 as threshold, since a 90 % packet delivery ratio can for example be used to determine transmission range of communication technologies, cf. [1].

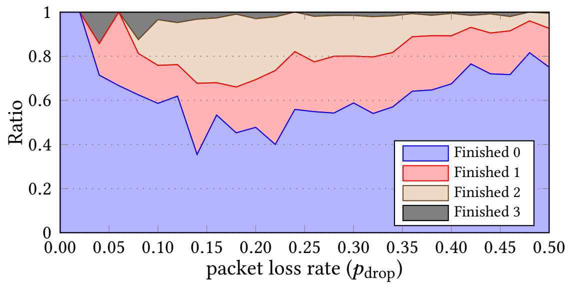

Figure 8: Number of completed maneuver containers before execution failure relative to all failed maneuvers, for $c^{\mathrm{cqm}} = 2$ and $t^{\mathrm{cqm}}_{\mathrm{rto}} = 20\,\mathrm{ms}$.

As a next step, studies should investigate mechanisms to judge deviations as critical or non-critical. For simple protocols, such deviations may be uncorrectable (without proposing extensions to the protocols) due to a lack of suitable messages. For example, with Hobert *et al.*'s [10] approach, the initiating vehicle has to wait for the CLC partner to send out the *lane change prepared* message after opening a gap. How long this will take is beyond the initiator's control; thus, the two vehicles' assumptions may differ. CVIP provides a way to check in with the other vehicle on its execution state by sending a new MSM. Another option may be to follow Sawade *et al.* [21] and not describe maneuvers too specifically in order to give some leeway for individual vehicles' executions. How to evaluate and possibilities to react to deviations will differ between protocols, and discussion about this aspect should be part of an overall assessment of communication protocols.

Lastly, researchers should compare different approaches for cooperative maneuver negotiation and execution against each other quantitatively to determine which protocols may be the most suitable ones under which conditions. These investigations should then also be backed by real-world experiments involving CAVs.

8 CONCLUSION

In this paper, we assessed maneuver failure modes and showed related mitigation mechanisms. Via an evaluation of CVIP, specifically of the negotiation and execution phase, we showed that mitigation concepts can increase maneuver success rates. Vehicles can negotiate maneuvers successfully despite high packet losses if they can resend individual messages. We concluded that CVIP can cope with PLR values expected from simulations. Overall, this paper sheds light on some of the challenges ahead for cooperative maneuvers and proposes ways to overcome them. Future research should further evaluate mitigation mechanisms and balance the inherent trade-offs to enable cooperative maneuvers for real-world deployments. Their successful implementation will increase the effectiveness and thus acceptance of automated vehicles.

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