LICENTIATE THESIS

Safety of Cooperative Automated Driving: Analysis and Optimization

Galina Sidorenko

Halmstad University | School of Information Technology
Licentiate Thesis | Halmstad University Dissertations no. 83

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Abstract

New cooperative intelligent transportation system (C-ITS) applications become enabled thanks to advances in communication technologies between vehicles (V2V) and with the infrastructure (V2I). Communicating vehicles share information with each other and cooperate, which results in improved safety, fuel economy, and traffic efficiency. An example of a C-ITS application is platooning, which comprises a string of vehicles that travel together with short inter-vehicle distances (IVDs).

Any solution related to C-ITS must comply with high safety requirements in order to pass standardization and be commercially deployed. Furthermore, trusted safety levels should be assured even for critical scenarios.

This thesis studies the conditions that guarantee safety in emergency braking scenarios for heterogeneous platooning, or string-like, formations of vehicles. In such scenarios, the vehicle at the head of the string emergency brakes and all following vehicles have to automatically react in time to avoid rear-end collisions. The reaction time can be significantly decreased with vehicle-to-vehicle (V2V) communication usage since the leader can explicitly inform other platooning members about the critical braking.

The safety analysis conducted in the thesis yields computationally efficient methods and algorithms for calculating minimum inter-vehicle distances that allow avoiding rear-end collisions with a predefined high guarantee. These IVDs are theoretically obtained for an open-loop and a closed-loop configurations. The former implies that follower drives with a constant velocity until braking starts, whereas in the latter, an adaptive cruise control (ACC) with a constant-distance policy serves as a controller. In addition, further optimization of inter-vehicle distances in the platoon is carried out under an assumption of centralized control. Such an approach allows achieving better fuel consumption and road utilization.

The performed analytical comparison suggests that our proposed V2V communication based solution is superior to classical automated systems, such as automatic emergency braking system (AEBS), which utilizes only onboard sensors and no communication. Wireless communication, enabling to know the intentions of other vehicles almost immediately, allows for smaller IVDs whilst guaranteeing the same level of safety.

Overall, the presented thesis highlights the importance of C-ITS and, specif-

ically, V2V in the prevention of rear-end collisions in emergency scenarios. Future work directions include an extension of the obtained results by considering more advanced models of vehicles, environment, and communication settings; and applying the proposed algorithms of safety guaranteeing to other controllers, such as ACC with a constant time headway policy.

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Contents

Acronyms

ACC adaptive cruise control

ADAS advanced driver assistance systems

AEBS automatic emergency braking system

AoI age of information

C-ITS cooperative intelligent transportation system

C-V2X cellular V2X

CACC cooperative adaptive cruise control

CAM cooperative awareness message

DENM decentralized environmental notification message

DSRC dedicated short-range communications

EEBL emergency electronic brake light

EM emergency message

IVD inter-vehicle distance

LTE long-term evolution

PCM platooning control message

TTC time to collision

URLLC ultra-reliable low latency communication

V2I vehicle-to-infrastructure

V2N vehicle-to-network

V2P vehicle-to-pedestrian

V2V vehicle-to-vehicle

V2X vehicle-to-everything

WHO World Health Organization

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1. INTRODUCTION

1.1 Motivation

According to the statistics of the World Health Organization (WHO) [1], around 1.3 million people lose their lives from traffic crashes each year. Due to improvements in traffic regulations and to road infrastructures (such as modern roundabouts, cycle lanes, 2+1 roads, traffic barriers, etc.), the number of fatal and non-fatal accidents in some developed countries has decreased during the last 20 years [2]. Nevertheless, globally, the cost of traffic accidents still makes up around 3% of countries' economy [3]. Even for Sweden, which has one of the lowest numbers of fatal road accidents, the cost of road crashes is estimated to be 2.6% of Sweden's GDP (data for 2017 [4]). Without a doubt, traffic safety problems cause considerable losses to individuals, their families, and the country's economy as a whole.

According to [5], at least 94% of all motor vehicle crashes are caused entirely or in part by human error. Among the main behaviors leading to accidents are inappropriate speeding, driving under the influence of alcohol or drugs, fatigue and sleepiness, and distraction (for example, through the use of mobile phones) [6].

Highly automated vehicles can almost eliminate the human error factor and thus significantly reduce the number of road accidents. Furthermore, communication between vehicles (vehicle-to-everything (V2X)) and between vehicles and infrastructure (traffic lights, road signs, etc.) (vehicle-to-infrastructure (V2I)) enables sharing data about involved road users, the surrounding environment, and traffic situations. It thus increases the awareness horizon for vehicles beyond line-of-sight. Through communication, coordinated decisions in complex traffic scenarios can be made by cooperative automated vehicles, which not only improves safety but also enhances efficiency on the roads through increased road utilization, reduced congestions, and emission of air pollutants [7; 8]. There are also economic benefits and reduced expenses concerned with the autonomous operation of vehicles with no drivers involved.

Whereas it might be too early to talk about the operation of fully autonomous vehicles on public roads, recent years have witnessed a modern, fast-paced development of vehicular technology, which shows an impressive trajectory forward for automation in transportation. The technology development is approaching, step-by-step, the final goal – fully self-driven and cooperative vehicles. Already now, in some scenarios, such as operating industrial vehicles in confined areas [9] or truck platooning in highways [10], almost total automation control is used without human involvement. Automated operation in confined areas and empty highways became a reality since the environment is well-defined and limited in possible scenarios. However, integrating automated vehicles in more complex and dynamic areas with pedestrians, cyclists, scooters, manual-driven vehicles, etc., is substantially more challenging from a safety perspective.

One of the typical for dynamic environment cases where automation can improve safety is rear-end collisions. Rear-end crashes are among the most frequently occurring types of collisions on the roads, accounting for approximately one-third of all crashes [11–13]. Statistics reveal that the most frequent reasons for rear-end collisions are tailgating, driver inattention, and visibility [11] that lead to a late driver response. Currently, on the market, there are a few commercially deployed advanced driver assistance systems (ADAS) intended to assist a driver in critical scenarios such as impendent collision. A typical example of such, AEBS, which is based on onboard sensors measurements (different combinations of radars, lidars, and cameras), reduces the risk of rear-end collisions or mitigates their consequences if the crash is unavoidable. However, according to statistics, only up to 70% of all rear-end collisions with personal injury could be avoided with such AEBSs [14]. V2V communication is a tool that can significantly help in preventing rear-end collisions since it allows receiving critical for decision information substantially faster than driver reaction time or response time of onboard sensors. Furthermore, onboard sensors can only sense in their line-of-site. Thus, automated systems based on their measurements can not perceive the impendent collision if the reason for braking is hidden by adjacent vehicles. Such systems are inferior to solutions based on wireless communication since, with the latter, the information about a potential rear-end collision can be received almost immediately, i.e., long before onboard sensors can register sufficient kinematic changes of the preceding vehicle.

For any solution related to vehicle automation to pass standardization and be incorporated into commercial vehicles, it must comply with high safety requirements. Furthermore, trusted safety levels should be assured.

Thus, the safety of automated solutions for preventing rear-end collisions in string-like vehicle formations needs to be analyzed and quantified. Such analysis should yield computationally efficient solutions suitable for real-time C-ITS applications.

1.2 Problem statement

This thesis focuses on the safety analysis of emergency braking scenarios for connected automated vehicles driving in a string formation. A typical example of such string formation is a *platoon* comprising a line of N ($N \geq 2$) vehicles driving closely behind each other. The first vehicle at the head of the platoon acts as the leader. The vehicles behind which are referred to as followers react and adapt to changes in the leader movement due to the use of automated driving systems and V2V communication. Current pilot on-road platoons typically consist of two to four trucks [15–18]. Thus, one can expect that short platoons comprised of 2-3 vehicles will be the most common type in the early stages of platooning integration to the public roads.

In the considered emergency braking scenarios, at some point the leader suddenly emergency brakes with its maximum braking capacity due to, for example, an unexpected obstacle on the road. Automated followers have to respond in time in order to stop and not collide with the preceding vehicle. Followers may have lower deceleration capability than their respective preceding vehicles, and the control response based on onboard sensors measurements may be comparatively slow. This puts a requirement on IVDs to be large enough to guarantee a no-collision behavior in emergency braking scenarios. With the use of V2V communication, the leader may transmit to followers emergency messages (EMs) with an explicit instruction to brake. Thus, the IVD ensuring safe braking may be shortened in comparison to the case when control is based only on onboard sensors (Fig.1.1). Reducing distances between consecutive vehicles implies better road utilization and traffic efficiency. Fuel consumption is also decreased with shortened IVDs for heavy-duty truck platoons [10; 16].

Obviously, even with quick propagation of information through V2V, IVDs cannot be reduced to zero, and there is some minimal boundary. In other words, if the leading vehicle starts emergency braking when the IVD between it and the follower has fallen below this allowed limit, the rear-end collision is unavoidable.

This licentiate thesis aims to study the conditions that guarantee safety in emergency braking scenarios for platoon-like formations. Methods and approaches for efficient computation of safety levels and safe IVDs are elaborated and presented in this study. "Safe IVD" can be defined as a distance that allows avoiding rear-end collisions in the case of emergency braking situations with a high probability. This probability of no-collisions, or level of safety, should be induced by desirable safety requirements and, naturally, is close to 1 for a safe system.

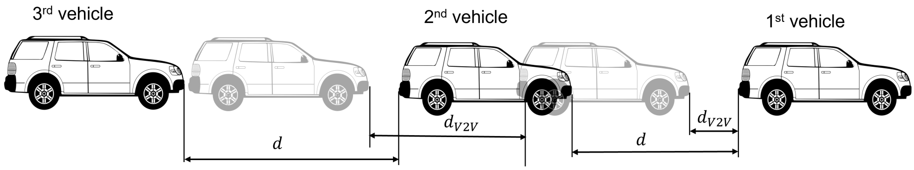

Figure 1.1: The benefits of using V2V communication are schematically shown in the picture. When V2V communication is used, the distance between consecutive cars is shortened while maintaining the same level of safety. For the presented three vehicles case, overall road occupancy is noticeably decreased.

1.3 Research questions

This section provides a collection of pertinent, more specific research questions based on the general problem formulation in Section 1.2. When it comes to safety analysis, the first straightforward question is:

- A. How to assess and quantify the safety of platooning formations in emergency braking scenarios?

This implies introducing and developing safety metrics or indicators that can quantify the safety in the system. Naturally, for a string of vehicles, such metrics should reflect the probability of rear-end collisions. Such metrics open up the possibility to estimate the safety level of a particular platooning system.

Several factors contribute to the safety level in emergency braking scenarios, one of which is distances between vehicles. Obviously, higher safety can be achieved with the increased IVDs, which, however, neglect road utilization and fuel consumption aspects. Decreased IVDs lead to better efficiency on the roads. Therefore, the following research question arises:

- B. What should be the minimum distances between vehicles, i.e., IVDs, to guarantee a predefined level of safety?

In platooning, different V2V communication schemes can be realized: decentralized and centralized, where in the latter, decisions are made by the central node, for example, the leader. The centralized schemes can result in better performance. Thus, considering the whole platoon as one entity, one can think about the next global optimization problem:

- C. How can the length or fuel consumption of the whole platoon be minimized while not jeopardizing safety?

V2V communication has a promising potential in preventing rear-end collisions. Its safety benefits can be quantified through a comparison with traditional onboard sensors-based systems. Such a comparison can be made in terms of minimum IVDs that allow avoiding rear-end collisions with a predefined high probability in emergency braking scenarios. It raises the following question:

- D. How much closer can vehicles safely drive to each other if they utilize V2V communication compared to the setting when only onboard sensors are used?

1.4 Contributions

The contributions of this thesis are directly related to the research questions introduced in section 1.3.

To make the safety analysis results applicable in practice, i.e., for real-time C-ITS applications, solutions have to be computationally efficient. For this reason, the main approach for dealing with posed research questions is chosen as analytical analysis. Compared to simulation-based approaches (like Monte-Carlo) or machine learning, theoretical analysis allows for explicit analytical solutions that are computationally efficient. The analytical approach is ubiquitous in the presented thesis.

Below, the contributions of all included papers are presented. In short, research question A results in safety metrics proposed in Papers I and II. In addition, the framework presented in Paper III allows for the calculation of a similar metric. Research question B is answered in Papers I, II, III under different assumptions: for an open-loop configuration in papers I-II and for a closed-loop configuration in III. Question C results in the centralized strategy for platooning presented in Paper I. Question D is considered in paper II where a comparison is made between the V2V solution and AEBS. Lastly, Paper IV shows an attempt of experimentally checking the results that were obtained in the other papers regarding questions B and D.

Paper I is the first in the line of the papers that provide a safety analysis for emergency braking scenarios involving consecutive vehicles. For N vehicles comprising a platoon, an open-loop configuration is considered. In this context, this means that after the leading vehicle starts emergency braking, followers continue to drive with a constant velocity until the onset of full braking initiated by receiving an EM from the leader. Under the introduced assumption, minimum safe inter-vehicle distances are analytically calculated as a function of the wireless channel characteristics. Furthermore, two emergency braking strategies for platooning based on V2V communication are designed. The first braking strategy is "decentralized" (or distributed) and assumes only local information. The second strategy – "centralized" – assumes centralized coordination by the leading vehicle and allows for the reduced overall whole platoon length/fuel consumption achieved through reducing braking capabilities of the intermediate vehicles in the platoon. Thus, the presented numerical example shows that the whole length of the 3-vehicle platoon can be reduced almost twice in the centralized approach compared to the distributed one: 16m in opposite to 32 m.

Paper II extends Paper I and further quantifies the benefits of using V2V communication compared to existing radar-based AEBS. Minimum safe IVDs that allow avoiding collisions with a predefined probability are obtained analytically for both the V2V setup and the AEBS case. It is shown that even under conservative assumptions on the V2V communication, such an approach significantly outperforms AEBS with an ideal radar sensor in terms of allowed IVDs. Thus, one of the numerical examples shows that for two identical vehicles travelling with an initial speed of 30 m/s even poor communication quality, i.e., packet loss probabilities $p_i = 0.81$, allows having the same IVD as in the AEBS case. However, with an improved quality of wireless communication link, i.e., having $p_i < 0.81$, the IVD between considered vehicles can be noticeably shortened. In typical AEBS, no harsh braking starts until a certain threshold of such metric as time to collision (TTC) is reached. A higher threshold implies a safer system but results in an increased number of false-positive braking. Lowering threshold leads to a less safe system and longer IVDs. V2V that provides the knowledge of plans and decisions of all involved vehicles enables avoiding such undesirable braking even for short IVDs.

Paper III, as opposed to papers I and II, considers a scenario with two consecutive vehicles in a closed-loop formation where the follower uses an ACC controller until the emergency message is received from the previous vehicle. For such configuration, maximum communication delay and corresponding minimum safe IVD that allows avoiding rear-end collision are analytically calculated. It is shown that the minimum safe IVD increases monotonically with the time until EM is received after the onset of braking for the leader. Naturally, the safe IVD is the smallest when the message is communicated instantly, and it is the largest in the limit when no communication is assumed. Furthermore, the results show that there is a finite time delay after which additional V2V communication does not provide improvement compared to the ACC-controller alone.

Paper III provides an explicit methodology for solving the considered safety analyses' problem. This approach implies three consecutive steps, where the first one results in the so-called "minimum safe braking set". Upon reaching this set, the follower vehicle has to emergency-brake immediately to avoid a rear-end collision. The obtained in the paper set can be directly used for emergency braking safety analysis for other types of controllers, i.e., other than the considered in the paper ACC. In addition, Paper III demonstrates how the proposed framework can be used to compute probabilities of no-collisions subject to packet losses of EMs.

Paper IV, as proof of concept, demonstrates the importance of wireless communication in preventing rear-end collisions. Experiments were carried out on small hand-assembled Arduino robots wirelessly communicating through ROS2 topics. A platoon of 3 robots was set up and run through emergency braking scenario experiments. The observed results have shown that wireless communication provides clear benefits in emergency braking scenarios. In more detail, stand-still distances (i.e., after a complete stop) between the robots were much longer if the leading robot wirelessly communicated critical information than when the robots-followers used only onboard sensors upon deciding on the start of the braking.

1.5 Organization of Thesis

The rest of the thesis is organized as follows. Background and literature review are presented in Chapter 2. Chapter 3 overviews the papers I-IV. Finally, Chapter 4 gives concluding remarks and discusses future directions.

2. Background and Related Works

2.1 Platooning

Platooning comprises a string of N, $N \geq 2$ vehicles that travel close together. The leader can be driven manually, and all others autonomously mimic the movement of the leader. Such operation is possible due to the usage of different sensors such as radars, lidars, cameras, etc., as well as V2V communication.

Platooning saves road space due to small IVDs, and thus increases the efficiency on the roads. Furthermore, as demonstrated in numerous experiments [10; 16; 17; 19], platooning decreases fuel consumption for heavy-duty vehicles due to decreased air drag force. In [19], results on fuel savings for the follower vehicle are presented for multiple platooning experiments. Numbers from 2% to 21% are reported there, which means that a truck can save up to 21% of the fuel if it follows another one in a platooning formation. The recent literature overview [10] of fuel economy in truck platooning states that those numbers can even be higher, up to 24%. Though followers experience the maximum fuel saving in a platoon, even the leading vehicle's fuel consumption decreases with a very short IVD and up to 5% of the fuel can be saved [10].

The most common objectives in platoon control are safety and stability, addressed by choosing a proper control strategy and relative spacing policy. Safety usually refers to the avoidance of rear-end collisions between consecutive vehicles, whereas stability usually refers to string stability.

Most of the early works on platooning were concerned with the concept of string stability. A platoon is considered to be string stable if disturbances of the velocity or position of the leading vehicle do not amplify as they propagate throughout the platoon. A recent unification of various definitions on string stability is provided in [20]. Platooning control strategies and related spacing policies that ensure string stability were addressed in many early works on string-stability [21–23]. The spacing policy implies the choice of desired, possibly time-varying, inter-vehicle distances. The most common choices of spacing policies for platooning formations are constant space and constant time gap policies. The former implies that the desired distance between vehicles is constant regardless of a change in speed, whereas in the latter, the desired distance is dependent on velocity in a linear manner. Some requirements for an ideal spacing policy are listed in [24]. Amongst those are guaranteed stability and string stability, but also further requirements such as smooth traffic flow and reasonable control effort. The constant time gap spacing policy, defined via relative position and velocity, is first described, followed by a proposed nonlinear ”ideal” spacing policy. In [25], the effect of a vehicle look ahead for the constant spacing policy is studied in the presence of ”parasitic lags”. Examples of nonlinear spacing policies are presented in [26; 27]. In [28; 29], delay-based spacing policies are introduced for guaranteed string stability subject to external disturbances.

Platooning control using common ACC is based on IVD and relative velocity measurements obtained by means of onboard sensors. Several ACC algorithms and their string stability conditions are presented and compared in [30]. Additional data shared by vehicles through wireless communication link extends the functionality of ACC to cooperative adaptive cruise control (CACC), which results in smaller IVDs. It has been shown that CACC allows maintaining string stability for time gaps significantly smaller than 1 s [31]. With V2V communication, such data as relative position information, vehicle acceleration, and velocity can be shared via a wireless link to improve platooning performance. Commonly used communication topologies in platooning are predecessor-following, bidirectional, bidirectional-leader, predecessor-following-leader [32], where the two latter imply direct communication with the leader.

Most of the research in platooning is focused on ensuring stability of a controller and improved safety by achieving string stability. However, in terms of safety, there is little work on ensuring safety and lower bounds on spacing policy in emergency braking scenarios when joint V2V communication is used. A literature overview on emergency braking in platooning is presented in Section 2.3.

2.2 Vehicle Communication

The current paradigm of the self-driving car manufacturers on enabling fully autonomous vehicles is mainly based on the line-of-sight sensors, such as radars, lidars, and cameras. Although driverless vehicles have been gaining media attention for more than a decade, recent news indicates that the topic has passed its peak hype. Many manufacturers have either postponed their commercial releases or are selling off their autonomous divisions due to safety issues [33–35]. Engineers and researchers put a lot of effort into developing technologies to overcome existing and expected safety issues.

One of the key technologies of safety enhancement in traffic is wireless communication [36]. Wireless communication enables vehicles to share information about their state (velocity, acceleration/deceleration, etc.) as well as observed information about road accidents, hidden pedestrians, or other hazardous conditions. It makes it possible to "see" what is going on behind a physical barrier or react to any situation with a delay much less than the human reaction time or response time of onboard sensors. For example, suppose the driver of a vehicle equipped with a C-ITS pushes the brakes due to a pedestrian suddenly appearing on the roadway. Such an event translates to the transmission of decentralized environmental notification messages (DENMs) about the emergency brake. In that case, all the involved surrounding vehicles will be almost immediately informed about the emergency braking since DENMs are received significantly faster than the processing time of the onboard sensors' measurements related to the emergency scenarios.

Similar to the postponement of self-driving vehicles' commercial launch due to safety-related issues, the readiness of wireless vehicular communication technologies is not yet there to serve advanced C-ITS and other mission-critical applications. Nevertheless, the wireless communication society is tirelessly expanding the horizons of the wireless vehicular communication theory, step-by-step implementing more and more advanced C-ITS applications and moving towards fast and reliable communication technologies.

Depending on the application of interest, there are many different acronyms for vehicular communication such as V2V, V2I, vehicle-to-pedestrian (V2P), vehicle-to-network (V2N), which are typically referred to under a general acronym V2X [37]. These acronyms mean the communication scenarios where at least one communicating vehicle is involved.

Currently, two different wireless technologies are considered to support V2X: cellular V2X (C-V2X) and ad hoc (or stand-alone) V2X. In the former case, communication happens through a cellular network, whereas in the latter, communication occurs directly between units without the involvement of a centralized network. One can notice the main disadvantage of C-V2X

– communication is possible only in the areas where cellular coverage exists. For ad hoc/stand-alone V2X, the communication infrastructure (i.e., base stations) is not necessary, and road users can communicate directly to each other everywhere. Therefore, the ad hoc V2X communication becomes suitable for cooperation between vehicles out of cellular coverage.

Nowadays, a few V2X protocols [38; 39] are already available for deployment and testing in different countries. For ad hoc V2X, the leading choice is made in favor of IEEE 802.11p dedicated short-range communications (DSRC)/ITS-G5 (G5 comes from frequency band 5.9GHz). For C-V2X, the protocol is within the long-term evolution (LTE) standard, which is sometimes referred to as LTE-V2X. Due to technological progress, those two alternatives have evolved and obtained corresponding successors, IEEE 802.11bd and 5G NR-V2X. The abbreviation NR stands for New Radio, i.e., the next generation of radio access technology after LTE. The last technologies are currently under extensive research.

It is expected that V2X communication will gradually increase its involvement in the day-to-day vehicular operation. Nowadays' V2X is ready to increase safety on public roads by extending the *information horizon for drivers* via IEEE 802.11p protocol [40]. It includes such C-ITS applications as stationary vehicle warning, emergency electronic brake light (EEBL), green light optimal speed advisory, road works warning, etc. In the future, the expected V2X services aim to extend the *awareness horizon for automated vehicles* on public roads and support platooning, CACC, cooperative maneuvering control, and collective perception. Since C-ITS applications depend on the wireless exchange of information, specific data messages have been defined. In Europe, the ETSI ITS standard defines such messages as cooperative awareness message (CAM) and DENM [41]. CAMs that are broadcasted by each vehicle repeatedly with a frequency between 1 and 10 Hz contain information about the location and status of the vehicle [42]. DENMs are event-triggered messages, which are broadcasted if some critical situation is detected.

One of the close to commercialization C-ITS applications is truck platooning. A V2V multi-brand truck platooning protocol is currently being developed within the European research project ENSEMBLE [43]. The project involves all major European truck manufacturers such as SCANIA, DAF, DAIMLER Ruck, IVECO, MAN, and VOLVO Group. The selected V2V communication standard in ENSEMBLE is ITS-G5. The deliverables of the ENSEMBLE project regarding the developed platooning protocol can be found in [44]. The document provides information about the specification of the V2X communication protocol, which enables platooning formation of vehicles using the ITS-G5 (or, in other words, IEEE 802.11p protocol). The protocol covers procedures needed for vehicles communication to form a platoon, the structure of messages required for driving in a platoon, joining, and leaving the platoon. Specified there, platooning control messages (PCMs) contain, amongst other information, the acceleration of the vehicle. All platooning vehicles broadcast PCMs every 50 ms, i.e., with a frequency of $f = 20$ Hz [44]. In the context of the presented research, PCM can be used as EM, which informs involved vehicles about emergency braking.

For effective and safe platooning control, ultra-reliable low latency communication (URLLC) becomes vital, especially in high-speed scenarios [39]. The V2V transmissions undergo channel impairments causing packet error losses, and packets are transmitted repeatedly for increasing reliability. There is a tight coupling between the performance of V2V communication link, e.g., channel quality, and the resulting safety. The thesis addresses this issue by proposing an analytical framework where the safe IVDs are determined given the communication quality (packet loss probabilities p_i).

2.3 Emergency Braking

Modern vehicles are often equipped with ADAS [45] helping a driver in regular (e.g., ACC, line keeping assistant, blind spot detection, etc.) and critical traffic conditions (e.g., AEBS [46], Collision Avoidance Systems, etc.). It is not uncommon for multiple systems to be installed on a vehicle.

AEBS is designed to reduce the risk of rear-end collisions or mitigate their consequences if the crash is unavoidable. Usually, AEBS possesses one or several "warning modes" and an additional "emergency braking phase." The former alert drivers when a dangerous situation is detected by audio or/and visual signal. Even slight braking can be automatically applied to draw the driver's attention. "Emergency braking phase" automatically starts if the driver does not respond to warnings.

In AEBS, such metric as TTC is often used for triggering "warning" and "emergency braking." The TTC is defined as the remaining time before rear-end collision happens if the speed and course of involved vehicles remain constant. Selection of a higher TTC-threshold implies more safety at the expense of a larger number of false positives brakes and an increased level of a nuisance for the driver. Selection of a lower threshold implies less safety level; thus, it might not be enough to prevent rear-end collisions, especially at high velocities. According to European regulations on advanced emergency braking systems [47], no emergency braking should start ”before TTC equal to or less than 3 s.” For some systems [48], as well as for non-assisted drivers [49], this threshold on hard braking initializing can be even lower than 2 s.

Introduction of V2V communications enables improvements of onboard sensors based ADAS to various C-ITS applications, for example, EEBL [50; 51]. With the latter, a vehicle broadcasts DENMs when its deceleration value reaches an emergency braking threshold value. Reception of the DENM by another vehicle triggers automatic emergency braking. The functioning of the EEBL depends on the reliability of the V2V communication channel – the higher the packet error rate is, the more DENMs repetitions are needed to inform other vehicles about the critical situation. In the context of platooning, so-called PCM can be used instead of DENM [43].

Different metrics can be used to assess safety in the traffic scenarios, i.e., to quantify collision detection and the probability of future collision. As mentioned above, TTC is a deterministic metric typically used for decision making in AEBS. Collision event becomes more probable with decreased TTC. Two surrogate measures of safety derived from TTC, namely, Time Exposed Time-to-collision (TET) and Time Integrated Time-to-collision (TIT), are proposed in [52]. Those safety indicators use vehicle trajectories collected over a specific time horizon for a certain roadway segment to calculate the overall safety indicator value. Vehicle-specific indicator values and safety-critical probabilities can be determined from the proposed safety measures. Rear-End Crash Risk Index (RCRI) is designed in [12] to quantify the potential of rear-end collisions. The proposed methodology is based on inductive loop detector data and enables identifying collision potentials in real-time. Based on information theory approaches, some common properties for metrics of functional safety are listed in [53]. In [54], continuous future risk function over time is introduced. It can be used for risk estimation, which is based on the predicted sequence of states of the relevant vehicles involved in a traffic situation.

Regarding emergency braking scenarios for platooning-like formations, the probability of collision is commonly used as a safety indicator. Such probability is directly determined by IVDs. The probability of rear-end collisions is estimated in [19] by calculating the overall stopping distance of a platoon leader and followers using Monte-Carlo simulations. In [55], various Monte Carlo simulations were carried out for different values of traffic speeds and pavement conditions to calculate the probability of multi-vehicle collision. Probabilistic distributions for reaction time, tyre performance, braking deceleration, and vehicle time gaps were considered. In [56], safe distance sets for heavy-duty vehicle platooning are numerically computed through a game theoretical framework. Communication delays are represented as changes in relative velocities between vehicles at the moment when braking is initiated by the leader. However, this approach is computationally expensive for real-time applications. Related simulation results for emergency braking are presented in [57].

To guarantee safety in emergency braking scenarios, several braking strategies were proposed in the literature. An emergency braking strategy is presented in [58], where the braking capability of the platoon is limited by the vehicle with the least deceleration capability. This idea is extended to a coordinated emergency brake protocol in [59] where vehicles form groups that brake together using the lowest common brake capability among the vehicles. A minimum safe time headway corresponding to this braking strategy is calculated using learning-based testing. According to the space-buffer scheme proposed in [60], platooning vehicles are required to be sorted in the order of increasing stopping distances. In [61], all vehicles brake synchronously, some milliseconds after the leader has sent an emergency brake command. It is assumed that all followers receive the braking message successfully during the introduced delay.

Approaches presented in this thesis are analytic and not based on simulations. Thus, they allow yielding computationally efficient solutions, e.g., minimum safe IVDs, that guarantee safety in emergency braking scenarios. New probabilistic safety metrics are also proposed in Papers I and II.

3. Summary of Appended Papers

This chapter provides a summary of the appended papers. Papers I-III provide safety analysis for emergency braking scenarios involving consecutive vehicles in a string or platooning-like formations, whereas Paper IV shows an implementation example of the obtained theoretical results on small mobile robots.

3.1 Paper I

Paper I is the first of those providing safety analysis for emergency braking scenarios involving consecutive vehicles. We investigate how V2V communication can be used to reduce inter-vehicle distances while guaranteeing safety in emergency braking scenarios. A heterogeneous platoon comprising N vehicles is under consideration. Each vehicle has a braking capacity $\bar{a}_i$, which may differ amongst the platooning members. For such a platoon, two modes of operation are considered: a *normal mode* and an *emergency braking mode*. In the *normal mode*, each vehicle in the platoon moves with the same constant speed v_0 in an unchanging environment. In the *emergency braking mode*, due to, e.g., some appearing obstacle on the road, the leading vehicle has to stop as fast as possible, which is performed by applying constant maximum deceleration $\bar{a}_0$ until standstill. Simultaneously with braking, the leader starts transmitting EMs to the other platooning vehicles over the dedicated communication channel using V2V communication. The EM informs the other platooning vehicles about the emergency braking situation, i.e., implicitly asking the receiving vehicle to enter the *emergency braking mode*. Reception of the EM by the i-th vehicle depends on communication channel quality, which is defined by a packet loss probability p_i.

This Paper I is focused on finding optimal IVDs that minimize the fuel consumption of the platoon moving in a *normal mode* at a certain predefined speed v_0, whilst not compromising safety in *emergency braking* situations. It is well known that reducing IVDs decreases air-drag, which, in turn, reduces fuel consumption [19]. On the contrary, close distances between vehicles pose safety issues and increase the risk of a rear-end crash.

By introducing safety metrics that assess safety in platooning and considering the dependence of air-drag force on the IVD, the objective of finding IVDs that are safe, as well as fuel-efficient, is reduced to an optimization problem, which is then considered in two different approaches.

In the first approach, *decentralized*, the objective function takes into account fuel consumption of each vehicle separately, whereas, in the second, *centralized*, the fuel consumption of all platooning vehicles is minimized simultaneously as a sum of the separate objective functions defined in the decentralized approach. Solutions for both approaches are presented in the paper, and corresponding minimum IVDs are derived for both cases. Those IVDs are defined by the braking capabilities of vehicles, velocity, and communication quality. It is worth mentioning that in the *centralized* approach, the generalized Lagrange multiplier method in the form of Karush–Kuhn–Tucker(KKT) conditions is used for deriving the solution.

Additionally, solutions of the optimization problems yield two emergency braking strategies for platooning based on V2V communication. In the decentralized strategy, every platooning vehicle determines its own safe distance to the vehicle in front and, in the case of an emergency braking situation, applies its maximum possible deceleration. In the centralized strategy, the braking capability of platooning vehicles should be reduced to some lower thresholds defined by the solution of the optimization problem. In this case, relevant data from all platoon members for deciding upon appropriate inter-vehicle distances for all trucks should be gathered centrally, e.g., by the platoon leader. Temporally reduced braking capabilities of the vehicles in the platoon allows for decreased inter-vehicle distances, which leads to better fuel economy and road space utilization.

To summarize, the centralized approach allows for global optimality, whereas the decentralized only allows for a local suboptimal solution. However, the decentralized solution can be used under a more relaxed communication setting, where local decision making is done based only on information from the preceding vehicle. Thus, global optimality is traded off against a more relaxed communication setting. The usefulness of the presented approaches is illustrated through several computational simulations.

3.2 Paper II

In the Paper II, we compare how safe emergency braking can be handled by V2V communication on the one hand and by AEBS based on radar measurements on the other. For this purpose, two different setups of platooning are considered. In the first one, platooning vehicles use EMs to obtain information about the emergency braking and the necessity to stop in order to avoid rear-end collisions. In the second setup, it is assumed that the platoon does not utilize V2V communication; instead, all vehicles in emergency braking scenario use AEBS based on onboard radar measurements. We consider simple AEBS where only the emergency braking phase is in place, and such metric as TTC is used as a trigger for entering emergency braking mode. A high TTC-threshold T_{AEBS} implies a safe system. However, this leads to a high number of false-positive braking. Thus, reasonable numbers for TTC-threshold T_{AEBS} have to be chosen by developing engineers.

For both setups, metrics characterizing the likelihood of a crash that link platooning operation to the safety requirements are derived. Through the introduced metrics, safety in platooning operation can be assessed directly. Those metrics define the maximum time delay when the vehicle has to switch to fully braking to avoid a rear-end collision with the preceding one. Furthermore, having the desired level of safety (i.e., the desired value of safety metric), minimum safe IVDs that allow avoiding the collision with given probability are obtained explicitly.

Several numerical simulations are performed and presented in the paper to support obtained theoretical results. Among those, minimum IVDs are calculated and compared for both setups – AEBS and V2V cases. In the latter, different quality of the wireless channel (through packet loss probabilities p_i) is considered.

The results demonstrate that especially for high velocities where it is critical to start braking early, V2V solution outperforms AEBS solution in terms of allowed IVDs even for non-reliable channel quality (e.g., for high packet loss probabilities). In opposite, mainly for low velocities, the radar-based approach allows for shorter IVDs in conditions with a poor V2V communication quality. It is worth mentioning that if TTC does not reach threshold T_{AEBS} through the entire braking process (which is typically for high velocities), collision is unavoidable at all without utilizing V2V communication. When vehicles are connected and communicate through V2V communication, they can start emergency braking upon receiving the EM, even if TTC is exceeding the prescribed threshold.

3.3 Paper III

Paper III provides an analytical form of the minimum safe IVD for emergency braking scenarios involving two vehicles and a constant distance policy ACC. Thus, compared to Paper I and Paper II, where followers were assumed to travel with a constant velocity until emergency braking, a closed-loop (vehicle controller-based) configuration is under consideration.

As in those two previous papers, two operation modes are considered: *normal* and *emergency braking*. In the *normal* mode, the follower uses ACC to follow the preceding vehicle with a short desirable IVD. Once the leader starts emergency braking, the follower resides in the normal mode during some communication delay τ^* s, i.e., until the EM is received, and after that enters emergency braking mode by applying maximum possible deceleration. Such EMs are generated by the leader with the onset of emergency braking and repeatedly sent to inform involved vehicles about the critical situation. The paper focuses on finding the dependency of minimum safe IVD on communication delay τ^*.

The considered scenario is split into three smaller subproblems showing the path to approach the presented research problem in a step-by-step manner:

- In the first subproblem, we define and analytically find a novel ”minimum safe braking set”. It comprises the two-dimensional hypersurface in a three-dimensional space of kinematic coordinates. If the dynamic parameters of the vehicles attain values in this set, the follower vehicle has to enter *emergency braking* mode immediately to avoid a rear-end collision. We emphasize that this set is a result in itself as it can be used for emergency braking safety analysis for other types of controllers, i.e., other than the considered here ACC.

- In the second subproblem, the explicit solution of trajectories for two vehicles on the interval $[0, \tau^*)$ (when the follower is still using ACC and has not yet entered emergency braking mode) is derived.

- Finally, the third subproblem combines the solutions of the subproblems above and yields an analytical expression of IVD such that when the follower uses the ACC for τ^* s, the system exactly attains the minimum safe set derived in the first subproblem.

The analytically obtained dependence of IVD on communication delay τ^* is monotonically increasing. Thus, the better V2V channel quality, the lower IVD is allowed between vehicles.

Numerical simulations presented in the paper demonstrate how much smaller the minimum IVD can be with an instant wireless communication compared to just using ACC. Further, there is a finite communication time delay overcoming which V2V does not bring any advantages over using only ACC; this is the result of control saturation. Lastly, this framework is expanded further, and the safety metric, i.e., no-collisions probability, is computed. Naturally, an increase in IVD increases the probability of safe braking (i.e., no collisions).

3.4 Paper IV

Paper IV demonstrates an implementation of an emergency braking scenario in a platoon consisting of small, hand-assembled mobile robots.

The goal of the simulation was to test the theoretical results on safe IVDs in platooning obtained in the previous papers and demonstrate a proof of concept. Whereas real-world field tests are desirable for the evaluation and verification of new ideas, they can be very costly. Using mobile robots allows checking hypotheses in a fast, non-expensive, and safe manner. A platoon of three robots with nearly identical weights and parts was set up. Each robot was based on Arduino and Raspberry Pi4 and ran Ubuntu, and specifically, ROS2 was used as a communication tool between platooning members. The front camera was used as an onboard sensor to determine the distance to the preceding robot, equipped with an AruCo marker.

The simulated scenario began with the platooning robots moving with almost constant speed in a *normal* mode. Then, at some moment of time, a key was manually pressed on the keyboard to instruct the leading robot to stop – i.e., to enter an *emergency braking* mode – simulating detection of some unexpected obstacle on the road. The followers then were supposed to stop without rear-end collisions. In the first group of experiments, followers used only onboard sensors to decide the moment to start braking. In the second group of experiments, the leading robot, after receiving the command to stop, sent through a dedicated ROS2 topic EMs to all of its followers with an explicit instruction to brake. As a result, in the second case, followers stopped almost immediately with the leader, whereas in the first one – the robots stopped almost touching each other. Although the inexpensive cameras used for the experiments were not capable of simulating vehicle radar systems to an acceptable level, the benefits of using wireless communication in emergency braking scenarios were clearly demonstrated. Another positive outcome of the conducted hardware experiments was revealing potential problems such as sensor errors that should be taken into consideration in future research.

The presented experiments were made within Halmstad University course that was taught in a novel approach, targeted toward training students to become researchers in the field of autonomous vehicles. This pedagogical approach is called *CAR* and combines *Creativity* theory, *Applied* demo-oriented learning, and *Real* world research context. However, pedagogical aspects of Paper IV are not relevant to the presented thesis.

4. Conclusions and Future Work

4.1 Conclusions

In this thesis, the benefits of using V2V communication in emergency braking scenarios for Cooperative Automated Driving, more specifically for a platoon-like formation of vehicles, are analyzed and quantified.

The conducted safety analysis yields computationally efficient methods and algorithms for calculating the minimum inter-vehicle distances that allow avoiding rear-end collisions in a string of vehicles with a high predefined guarantee. These IVDs are theoretically obtained for an open-loop (Paper I) and a closed-loop (Paper III) configurations, where in the latter, ACC with a constant-distance policy serves as a controller.

The presented safe IVDs are explicitly dependent on the wireless connectivity quality through corresponding packet loss probabilities. Degraded performance of wireless communication links, i.e., when many repetitions of messages are required in order to successfully deliver information of the emergency braking situation, results in larger safe IVDs whereas better connectivity conditions allow for smaller IVDs. A comparison between the proposed V2V communication-based solution and the classical AEBS which is based on onboard sensors measurements, is performed in Paper II. The results show that the proposed solution based on V2V connectivity outperforms the radar-based case in terms of minimum allowed IVDs even for relatively poor communication quality. This is especially observable for high speeds.

The provided methodology allows obtaining safety guaranteeing conditions not only in the spatial domain, i.e., as IVDs, but also in the temporal. This is manifested in the computational maximum communication delay. In this sense, this thesis provides results that can be used to develop control and communication policies for Cooperative Automated Driving applications.

The thesis provides explicit, analytic, and computationally efficient guarantees for safe cooperative driving of consecutive vehicles. Overall, the presented results show the important role of V2V communication for improved safety in critical traffic scenarios where onboard sensors might not respond fast enough to prevent serious consequences. This argues for the importance of C-ITS and, specifically, V2V in preventing rear-end collisions in emergency scenarios.

4.2 Future work directions

I see several promising directions for extending and expanding the results presented in this thesis. One of such future work directions is considering more advanced vehicle dynamics and environment models. With more realistic modelling, one can expect to obtain more accurate bounds on spacing policies. More precisely, the following options can be considered:

- Incorporation of more realistic dynamic models of vehicles, e.g., time-varying decelerations;
- Incorporation of more realistic environment models, e.g., time-varying road slopes, curves;
- Consideration of more realistic sensor models where error measurements are taken into account;

Another interesting expanding line of the research is to add more physical details of signals propagation to the considered communication setting. This can be done with the help of various channel models for calculating packet loss probabilities p_i. Such models include geometry-based [62; 63], stochastic [64; 65], and geometry-based stochastic channel models [66].

The results of this thesis were obtained under IEEE 802.11p consideration. Having IEEE 802.11p as a standard for V2V, communication quality represented via p_i, primarily depends on two factors: deterioration of signals due to channel propagation and interference caused by packets collisions from communicating nodes. Extending this work to C-V2X is planned since the dedicated scheduler can effectively utilize radio resources, potentially lowering the communication latency. This makes C-V2X more perspective for handling mission-critical applications. In C-V2X, the modelling of packet loss probabilities should take into account dependency on the scheduling strategy, distance from the base station, number of communicating vehicles in the range of the base station, etc.

Independent of the used V2V communication technology, in conditions when the wireless connectivity is completely not available, the platoon should switch to the onboard sensors-based control, which in turn means increasing of IVDs in most cases. Using both available systems - onboard and wireless-based - that should back up each other for an increased safety is a foreseeable practical approach. Developing algorithms for a fusion of those two systems is another direction for future work.

The proposed methodology of safety analysis for emergency braking scenarios can be applied to other types of controllers (other than constant distance space policy ACC). One of the straightforward choices is an ACC with a constant time headway policy. In such a setting, explicit or computationally efficient numerical solutions should be found and investigated to find tighter bounds on the inter-vehicle spacing policy. In addition, the results obtained for a two vehicles case can be generalized for platoons with an arbitrary number of vehicles using a procedure similar to the backstepping control design for cascade systems [67; 68]. For the considered controllers, the safety analysis can be done in the space or time domain, where the latter implies the usage of the maximum allowed communication delays. Furthermore, communication delays can be replaced by a more general approach, which takes the overall age of information (AoI) into account [69]. AoI is a metric that uses freshness of available by followers information and is different from commonly used delay and latency. This metric is currently receiving quite a bit of attention from part of the research community [70].

Apart from the directions mentioned above, the present study can be extended to more complex traffic scenarios such as intersections and roundabouts. In such scenarios, a high level of planning combining control and communication should be done where all road users and infrastructure can be seen as multiple interacting intelligent agents. Solutions for such planning must comply with safety requirements. One promising tool for approaching complex traffic scenarios is machine learning.

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Appendix

The following papers, referred to in the text by their Roman numerals, are mentioned in the thesis.

PAPER I: **Vehicle-to-Vehicle Communication for Safe and Fuel-Efficient Platooning**
Galina Sidorenko, Johan Thunberg, Katrin Sjöberg, Alexey Vinel. 2020 IEEE Intelligent Vehicles Symposium (IV), pp. 795-802, doi: 10.1109/IV47402.2020.9304719

PAPER II: **Safety of Automatic Emergency Braking in Platooning**
Galina Sidorenko, Johan Thunberg, Katrin Sjöberg, Aleksei Fedorov, Alexey Vinel. IEEE Transactions on Vehicular Technology, 2021, early access, doi: 10.1109/TVT.2021.3138939

PAPER III: **Emergency braking with ACC: how much does V2V communication help?**
Galina Sidorenko, Daniel Plöger, Johan Thunberg, Alexey Vinel, IEEE Networking Letters, 2022, *submitted*.

PAPER IV: **The CAR Approach: Creative Applied Research Experiences for Master's Students in Autonomous Platooning**
Galina Sidorenko, Wojciech Mostowski, Alexey Vinel, Jeanette Sjöberg, Martin Cooney. 30th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2021, pp.214-221, doi: 10.1109/RO-MAN50785.2021.9515560