



DOCTORAL THESIS

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# Cooperative Automated Driving for Enhanced Safety and Ethical Decision-Making

Galina Sidorenko



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Cooperative Automated Driving for Enhanced Safety and Ethical Decision-Making  
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# Abstract

Advances in technologies for vehicular communication enable new applications for Cooperative Intelligent Transportation Systems (C-ITS). Communicating vehicles share information and cooperate, which allows for improved safety, fuel economy, and traffic efficiency. Platooning – a coordinated string of vehicles with small Inter-Vehicle Distances (IVDs) – comprises one such C-ITS application. Any C-ITS application must comply with high safety requirements to pass standardization and be commercially deployed. Moreover, trusted solutions should be guaranteed even for critical scenarios or rare edge cases.

This thesis presents two sets of contributions related to cooperative automated driving. Firstly, it provides conditions ensuring safe platooning or vehicle following. Secondly, it introduces an ethical framework to guide autonomous decision-making in scenarios involving imminent collisions.

In the first set of contributions, we consider emergency braking scenarios for vehicles driving in a platoon or following each other. In such scenarios, the lead vehicle suddenly brakes. This requires swift responses from followers to prevent rear-end collisions. Here, Vehicle-to-Everything (V2X) communication has the potential to significantly reduce reaction times by allowing the lead vehicle to notify followers of the emergency braking. The presented safety analysis yields computationally efficient methods and algorithms for calculating minimum IVDs for rear-end collision avoidance. The IVDs are computed for closed-loop and open-loop configurations. The open-loop configuration implies followers drive with a constant velocity until the onset of braking, whereas in the closed-loop configuration, a controller is used under some restrictions. In addition, a centralized approach for optimization of IVDs in platoon formations is carried out. Such an approach allows for improved fuel consumption and road utilization. An analytical comparison shows that our proposed Vehicle-to-Vehicle (V2V) communication-based solution is superior to classic automated systems, such as automatic emergency braking system, which utilizes only onboard sensors. Wireless communication provides intentions to vehicles almost immediately, which allows for smaller IVDs while guaranteeing the same level of safety.

In the second set of contributions, an ethical framework to guide autonomous decision-making is presented. Even though collisions resulting from edge

cases are unlikely, it is essential to address them in motion planning logic for autonomous vehicles. Decisions made in such situations should always prioritize ethical considerations, such as saving human lives. Adhering to ethical principles in the development and deployment of autonomous vehicles is essential for fostering public understanding and acceptance. The thesis presents a framework of ethical V2X communication, where V2X is acknowledged as an essential means for enabling autonomous vehicles to perform coordinated actions to meet certain ethical criteria. The presented framework demonstrates how the risk or harm resulting from unavoidable collisions can be mitigated or redistributed under ethical considerations through cooperation between vehicles.

Overall, the presented thesis highlights the importance of C-ITS and, specifically, V2X communication in managing emergency scenarios. V2X communication enables faster response times and facilitates cooperative maneuvers, which helps preventing rear-end collisions or mitigating their consequences under ethical considerations. 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 frameworks to more complicated traffic scenarios.

# Preface

This doctoral thesis consists of two parts. Part I gives an overview of the research field and serves as an introduction to the main scientific work, which is composed of six papers and is presented in Part II. The following papers, referred to in the text by their Roman numerals, are included in this thesis:

**PAPER I: Towards a Complete Safety Framework for Longitudinal Driving**

Galina Sidorenko, Aleksei Fedorov, Johan Thunberg, Alexey Vinel.  
*IEEE Transactions on Intelligent Vehicles*, 2022, vol. 7, no. 4,  
pp. 809-814, doi: 10.1109/TIV.2022.3209910

**PAPER II: Emergency braking with ACC: how much does V2V communication help?**

Galina Sidorenko, Daniel Plöger, Johan Thunberg, Alexey Vinel.  
*IEEE Networking Letters*, 2022, vol. 4, no. 3, pp. 157-161,  
doi: 10.1109/LNET.2022.3190244

**PAPER III: 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 IV: Safety of Automatic Emergency Braking in Platooning**

Galina Sidorenko, Johan Thunberg, Katrin Sjöberg, Aleksei Fedorov, Alexey Vinel. *IEEE Transactions on Vehicular Technology*, 2022, vol. 71, no. 3, pp. 2319-2332,  
doi: 10.1109/TVT.2021.3138939

**PAPER V: Ethical V2X: Cooperative Driving as the Only Ethical Path to Multi-Vehicle Safety**

Galina Sidorenko, Johan Thunberg, Alexey Vinel. 2023 *IEEE 98th Vehicular Technology Conference (VTC2023-Fall)*, 2023, doi: 10.1109/VTC2023-Fall60731.2023.10333432

**PAPER VI: Cooperation for Ethical Autonomous Driving**

Galina Sidorenko, Johan Thunberg, Alexey Vinel. 2023, *submitted*.

During my PhD studies, I have also contributed to the following papers, which are not included in the thesis:

- **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

- **Efficiently Bounding the Probabilities of Vehicle Collision at Intelligent Intersections**

Johan Thunberg, Galina Sidorenko, Katrin Sjöberg, Alexey Vinel. *IEEE Open Journal of Intelligent Transportation Systems*, 2021, vol. 2, pp. 47-59, doi: 10.1109/OJITS.2021.3058449

- **Cooperative Vehicles versus Non-Cooperative Traffic Light: Safe and Efficient Passing**

Johan Thunberg, Taqwa Saeed, Galina Sidorenko, Felipe Valle, Alexey Vinel. *Computers*, 2023, vol. 12, no. 8, 154, doi: 10.3390/computers12080154.

- **Offloading Platooning Applications from 5.9 GHz V2X to Radar Communications: Effects on Safety and Efficiency**

Elena Haller, Galina Sidorenko, Oscar Amador, Emil Nilsson. *The Thirteenth International Conference on Advances in Vehicular Systems, Technologies and Applications: VEHICULAR 2024*, March 2024, *accepted*.

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I extend my gratitude to all my colleagues at the School of Information Technology for the great and inspiring working environment. I also thank Halmstad University and the School of Information Technology for providing me with such an excellent opportunity to conduct research on the hot topic of autonomous driving, as well as for providing a comfortable and motivating workplace.

Last but not least, I thank my beloved family for their strong everyday support and never-ending belief in my ability to complete the work. This has been a constant source of encouragement and motivation.



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# Acronyms

<b>ACC</b>	Adaptive Cruise Control
<b>ADAS</b>	Advanced Driver Assistance Systems
<b>AV</b>	Autonomous Vehicle
<b>AEBS</b>	Automatic Emergency Braking System
<b>AoI</b>	Age of Information
<b>APB</b>	Automatic Preventive Braking
<b>C-ITS</b>	Cooperative Intelligent Transportation Systems
<b>C-V2X</b>	Cellular V2X
<b>CACC</b>	Cooperative Adaptive Cruise Control
<b>CAM</b>	Cooperative Awareness Message
<b>DENM</b>	Decentralized Environmental Notification Message
<b>DSRC</b>	Dedicated Short-Range Communication
<b>EEBL</b>	Emergency Electronic Brake Lights
<b>EM</b>	Emergency Message
<b>IVD</b>	Inter-Vehicle Distance
<b>KKT</b>	Karush–Kuhn–Tucker
<b>LTE</b>	Long-Term Evolution
<b>RCRI</b>	Rear-End Crash Risk Index
<b>RSS</b>	Responsibility-Sensitive Safety
<b>SFF</b>	Safety Force Field
<b>TET</b>	Time Exposed TTC
<b>TIT</b>	Time Integrated TTC
<b>TTC</b>	Time to Collision
<b>URLLC</b>	Ultra-Reliable Low Latency Communication
<b>V2I</b>	Vehicle-to-Infrastructure
<b>V2N</b>	Vehicle-to-Network

**V2P**    Vehicle-to-Pedestrian  
**V2V**    Vehicle-to-Vehicle  
**V2X**    Vehicle-to-Everything

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# **Part I**

## **Overview**



# 1. INTRODUCTION

## 1.1 Motivation

About 94% of all motor vehicle crashes on the roads are caused entirely or in part by human error [1]. Highly automated vehicles can almost eliminate the human error factor and thus significantly reduce the number of road accidents. Furthermore, vehicular communication, such as communication between vehicles (V2V) and with infrastructure (Vehicle-to-Infrastructure (V2I)), including traffic lights, road signs, etc., 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 congestion, and decreased emissions of air pollutants [2; 3]. There are also economic benefits and reduced expenses associated with the autonomous operation of vehicles with no drivers involved.

There have been optimistic forecasts about the rapid integration of fully Autonomous Vehicles (AVs) into public roads. Over time, developers and researchers have gained a clearer understanding of the challenges associated with the development of AVs, especially in terms of ensuring safety, addressing ethical considerations, and navigating regulatory frameworks. This awareness has shifted the evolution of autonomous vehicle technology from the pursuit of fully AVs to a deeper focus on Advanced Driver Assistance Systems (ADAS) and gradual automation.

Although it might be too early to talk about the operation of fully AVs on public roads, recent years have witnessed an incremental, fast-paced development of vehicular technology, which shows an impressive trajectory forward for automation in transportation. Already now, in some scenarios, such as operating industrial vehicles in confined areas [4] or truck platooning at highways [5], almost complete automation control is used without human involvement. Automated operation in confined areas and empty highways is now possible in well-defined and limited scenarios. However, the integration of automated vehicles in more complex and dynamic areas with pedestrians, cy-

clists, scooters, manual-driven vehicles, etc., is substantially more challenging from a safety perspective.

In dynamic scenarios, rear-end collision is a typical accident where automation can improve safety. Rear-end crashes are among the most frequently occurring types of collisions on the roads, accounting for approximately one-third of all collisions [6–8]. Statistics reveal that the most frequent reasons for rear-end collisions are tailgating, driver inattention, and poor visibility [6], all of which contribute to a late driver response. Currently, on the market, there are a few commercially deployed ADAS intended to assist a driver in critical scenarios such as impending collision. A typical example of such, Automatic Emergency Braking System (AEBS), which is based on onboard sensors measurements (with 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 [9]. V2X communication is a technology that can significantly help in preventing rear-end collisions since it provides critical for decision-making information substantially faster than driver reaction times or response times of onboard sensors. Furthermore, onboard sensors can only sense within their line-of-site range. Thus, automated systems relying solely on these measurements may not perceive an impending collision due to occluding adjacent vehicles. In this sense, such systems are inferior to solutions based on wireless communication where information about a potential rear-end collision can be received almost immediately, i.e., long before onboard sensors can register sufficient kinematic changes of a 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 needs to be analyzed and quantified. Such analysis should yield computationally efficient solutions suitable for time-critical C-ITS applications.

Even though autonomous decision-making may properly manage road situations where humans make errors, still, there are situations where accidents are challenging or even impossible to prevent [10; 11]. Thus, even according to the most optimistic assessment, only 90% of traffic accidents can be eliminated by AVs. Critical situations may arise due to limitations in sensing capabilities [12]. Other challenging scenarios include unsafe human behavior, for example, hazardous driving styles exhibited by human drivers (in mixed traffic conditions) or spontaneous actions of cyclists or pedestrians [13; 14]. These edge cases are considered very unlikely but yet present, and AVs must know how to respond to them. As generally agreed upon, this response should

adhere to ethical principles [10].

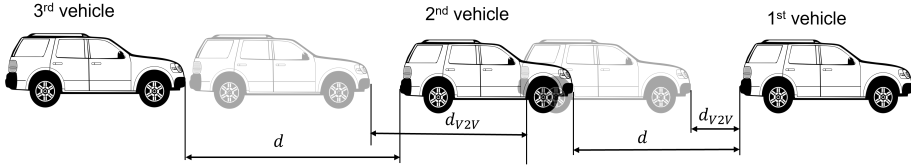
The following section narrows down the specific research problems addressed within this thesis. Before proceeding further, we provide some remarks to facilitate smoother reading. Firstly, by "cooperative" we refer to wirelessly connected vehicles with the capability to exchange information for the sake of enhancing their perception or coordination of their maneuvers. Secondly, within the thesis, unless explicitly stated, we use the terms "automated" and "autonomous" vehicles interchangeably, since we generally abstract from human interventions in the analysis and presented results. When referring to autonomous vehicles, it is essential to bear in mind that the obtained results can, with some remarks, be applied to automated driving systems. Thirdly, "V2X-communications" is a well-defined term and refers to a broad set of communicating entities in C-ITS. Sometimes, when we want to emphasize specific communicating entities, we use other abbreviations, e.g., V2V to explicitly refer to inter-vehicular communications.

## 1.2 Problem Statement

This thesis focuses on two linked topics: first, the safety analysis of emergency braking scenarios for cooperative automated vehicles driving in a string formation or following each other; and second, the mitigation of accident outcomes when the required safety guarantees are not maintained.

A typical example of a string formation is a *platoon* comprising  $N$  ( $N \geq 2$ ) vehicles driving closely behind each other. The first vehicle at the head of the platoon acts as the leader. The vehicles behind, referred to as followers, react and adapt to changes in the leader's movements through 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 comprising two to three 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. Followers have to respond in time in order to stop and not collide with the preceding vehicle. Followers may have lower deceleration capabilities than their respective preceding vehicle, and the control response based on measurements from onboard sensors may be comparatively slow. This puts a requirement on IVDs to be large enough to guarantee collision-free behavior in emergency braking scenarios. By using V2V communication, the leader may transmit to followers Emergency Messages (EMs) with an explicit instruction to brake. Thus, the IVDs ensuring safe braking may be shortened in comparison to control approaches based on



**Figure 1.1:** The benefits of using V2X communication are schematically shown in the picture. When V2X communication is used, the distance between consecutive vehicles is shortened while maintaining the same level of safety. For the presented case with three vehicles, overall road occupancy is noticeably decreased.

onboard sensors only (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 [5; 16].

Even with quick propagation of information through V2X, IVD cannot be reduced to zero, and there is some minimal limit or bound. In other words, if the leader starts emergency braking when the IVD to its follower has fallen below this allowed limit, rear-end collision is unavoidable.

In this thesis, we aim to study the conditions that guarantee safety in emergency braking scenarios where automated vehicles drive in a platooning formation or follow each other. We aim to propose methods and approaches for efficient computation of safety levels and safe IVDs. "Safe IVD" can be defined as a distance between moving vehicles that allows to avoid 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.

Furthermore, if for any reason the safety guarantees are not maintained and a collision becomes unavoidable, its severity needs to be quantified and, if possible, reduced. Although such corner cases for highly automated vehicles are considered very rare, the widespread adoption of AVs hinges on their resolution. Thus, instead of refusing to accept the possibility of accidents for AVs, there is a need to focus on how to ensure the best outcome in the event of an accident. Such considerations should take into account ethical aspects, such as minimizing the severity of the accident or redistributing it among the involved actors fairly. As a second research topic closely related to the first, this thesis further aims to explore resolutions of ethical dilemmas for cooperative automated vehicles in scenarios where collisions might be unavoidable.

## 1.3 Research Questions

This section provides specific research questions based on the general problem formulation in Section 1.2. Regarding the safety analysis, our first research question is:

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

Longitudinal driving refers to a vehicle's motion along its longitudinal axis, particularly in scenarios where the vehicle is driving in a platoon or follows another vehicle. Research question A implies introducing and developing safety indicators or metrics that can quantify the safety of the system. Naturally, for a string of vehicles, such metrics should reflect the probability of rear-end collisions. These safety metrics provide a means for quantifying 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 consecutive vehicles (IVDs). Higher safety can be achieved with increased IVDs, which, however, neglects road utilization and fuel consumption aspects. Decreased IVDs allow for better efficiency on the roads. However, there exist lower bounds for such IVDs. Therefore, the second research question is:

- 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 scheme can yield better performance compared to the decentralized one. When considering the whole platoon as one entity, a natural (global) optimization problem arises, addressed by the following research question:

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

V2X communication has the potential to prevent rear-end collisions. The safety benefits can be quantified through a comparison with traditional onboard sensor-based systems. Such comparison can be made in terms of the minimum IVDs that allow avoiding rear-end collisions with a predefined high probability in emergency braking scenarios. This raises the following question:

- D. How much closer can vehicles safely drive to each other if they utilize V2X communication compared to the setting when only onboard sensors are used?

The four research questions above are related to safety guarantees. However, in cases where safety guarantees are not maintained, and a collision between vehicles becomes unavoidable, its severity should be quantified and, if possible, minimized by taking into account ethical considerations. This gives rise to the following two research questions:

- E. How to quantify the severity of an imminent accident in a cooperative multi-vehicle scenario?
- F. How can V2X communication be utilized for resolution of ethical dilemmas in multi-vehicle scenarios?

In the subsequent section, the contributions of this thesis are presented with respect to these six research questions.

## 1.4 Contributions

To make safety analysis results applicable in practice, i.e., for time-critical C-ITS applications, solutions have to be computationally efficient. We use an analytical approach to address the research questions posed in Section 1.3. Compared to simulation-based (such as Monte Carlo) or data-driven approaches (involving various machine learning techniques), our approach allows for explicit analytical solutions that are computationally efficient. This analytical approach is ubiquitous in the presented thesis.

Below, the contributions of the appended papers are presented. In short, to address research question A, safety metrics are proposed in Papers III and IV. In addition, the framework presented in Papers I and II allows for the calculation of a similar metric. Research question B is answered in Papers I, II, III, IV under different assumptions: for a closed-loop configuration in Papers I-II and for an open-loop configuration in Papers III-IV. Research question C is addressed by the centralized strategy for platooning in Paper III. Research question D is addressed in Paper IV, where a comparison is made between V2X-based solution and AEBS. Research question E is addressed by the accident severity metrics proposed in Papers V and VI. Research question F is addressed in Papers V and VI, where a concept of ethical V2X is formulated as a means for resolving dilemmas in multi-vehicle scenarios under ethical considerations.

We should also highlight that the results obtained in Paper I are general in the sense that they can be applied to a wider scope of applications than connected vehicles. Paper I provides a foundation for the progression of our research on safety of longitudinal driving. Safety is defined as the guaranteed

avoidance of rear-end collisions if the maximum response time of the vehicle is bounded. This response time may encompass delays associated with perception through onboard sensors or through V2X communication.

Papers I and II provide a safety analysis for emergency braking scenarios for two consecutive vehicles in a closed-loop configuration. We refer to the two considered vehicles as the leader (leading vehicle) and the follower (following vehicle). The longitudinal distance between two moving vehicles is considered safe if the follower can avoid a collision even if the leader abruptly applies full braking force. The sole means for avoiding collisions for the follower is braking; lateral maneuvers are not taken into account.

Paper I enhances and generalizes the well-known Responsibility-Sensitive Safety (RSS) model [19]. The RSS model provides a computationally efficient procedure for the calculation of safe longitudinal inter-vehicle distances based on the response time of the follower. The RSS formulas [19] are obtained by considering an emergency braking scenario where the leader suddenly brakes. The response time  $\tau$  refers to the time it takes for the follower's control system to react to an impending collision. It is the time from the onset of the leader's braking to the time when the follower applies full braking force. The RSS model demonstrates a conservative approach by assuming the "worst case scenario", meaning that the follower accelerates at a constant rate during its response time. Paper I enhances the RSS model for longitudinal driving by covering the situation where the follower has a higher decelerating capacity than the leader. Furthermore, Paper I generalizes the RSS model by substituting the conservative RSS assumptions with an arbitrary follower's acceleration/deceleration profile  $h(t)$ . This means that instead of assuming that the follower applies a constant acceleration during the response time, Paper I derives minimum safe IVDs under more realistic assumptions. Knowledge of the follower's profile, such as accelerating/decelerating and jerk intervals, allows for smaller safe IVDs compared to the bounds obtained under the RSS assumptions. Additionally, Paper I shows how the proposed framework can be applied by substituting real and possibly computationally intractable acceleration/deceleration profiles with upper-bounding functions. This is done in a way such that equivalent safety guarantees for the upper-bounded system are reached at the expense of larger inter-vehicular distances. Substituting the real profile  $h(t)$  with a computationally more tractable function  $g(t)$  increases the required minimum safe distance but allows for easier derivation. The closer the function  $g(t)$  approximates  $h(t)$ , the closer the obtained bound is to the true IVD derived for  $h(t)$ .

The results in Paper I are obtained by introducing a novel three-step methodology for solving the considered safety analysis problem. This approach contains three consecutive steps. In the first step, the so-called "minimum safe

braking set" is derived. Upon reaching this set, the follower has to emergency brake immediately to avoid a rear-end collision. In the second step, the trajectories of the two vehicles during the response time interval are constructed. Finally, in the third step, the minimum initial distance between vehicles is found such that trajectories obtained in the second step reach the "minimum safe braking set" exactly at the end of the response time.

Paper II presents an example of how the three-step methodology can be applied to the case where vehicles use Adaptive Cruise Control (ACC) along with additional V2X communication. In the considered emergency braking scenario, the leader simultaneously with the onset of braking starts repeatedly transmitting EMs to the follower. These EMs notify the involved vehicle about the emergency braking situation. The follower uses an ACC controller until the EM is received, and then applies the maximum possible deceleration. For such a configuration, maximum communication delay and corresponding minimum safe IVD that allow avoiding rear-end collision are calculated analytically. Unlike Paper I, the resulting minimum safe distances are calculated for a state-dependent controller without explicitly representing it as a function of time. It is shown that the minimum safe IVD increases monotonically as a function of the time it takes for EM to be received after the onset of the leader's braking. 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 V2X communication does not provide improvement compared to the ACC-controller alone. In addition, Paper II demonstrates how one can compute probabilities of no-collisions subject to packet losses of EMs.

Paper III provides a safety analysis for emergency braking scenarios involving  $N$  consecutive vehicles. For  $N$  vehicles comprising a platoon, an open-loop configuration is considered. In this context, this means that after the leader starts emergency braking, followers continue to drive with a constant velocity until the onset of full braking, which is initiated by the reception of an EM from the leader. Under the introduced assumption, minimum safe IVDs 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 leader and enables reduced overall platoon length/fuel consumption. This is achieved by reducing the braking capabilities of the intermediate vehicles in the platoon. A presented numerical example shows how the total length of a three-vehicle platoon is significantly reduced when using the centralized approach instead of the distributed one. The total sum of IVDs is 16 m for the centralized approach and

32 m for the distributed one.

Paper IV extends Paper III and further quantifies the benefits of using V2X communication compared to existing radar-based AEBS. Minimum safe IVDs that allow avoiding collisions with a predefined probability are obtained analytically for both the V2X setup and the AEBS case. It is shown that even under conservative assumptions on the V2X communication, our approach significantly outperforms AEBS with an ideal radar sensor in terms of allowed IVDs. One of the numerical examples shows that for two identical vehicles moving with an initial speed of 30 m/s, even poor communication quality with packet loss probabilities  $p_i = 0.81$  allows for the same IVD as AEBS. However, with an improved quality of the wireless communication link, i.e., with packet loss probabilities  $p_i < 0.81$ , the IVD between the considered vehicles can be noticeably shortened. In typical AEBS, no harsh braking starts until a certain threshold of a metric such as Time to Collision (TTC) has been reached. A higher threshold implies a safer system but results in an increased number of false-positive brakes. A lower threshold leads to enhanced driver comfort at the expense of a lower level of safety. V2X that provides the knowledge of plans and decisions of all involved vehicles enables avoiding such undesirable braking, even for short IVDs.

If, for any reason, safe distances between vehicles are not kept and a collision is unavoidable, its severity needs to be quantified and minimized (if possible) by taking into account ethical considerations. Papers V and VI delve into this matter by exploring metrics to characterize accident severity in multi-vehicle scenarios. With an information exchange between the vehicles via V2X, the calculation of such metrics becomes possible. This, in turn, can help the involved autonomous vehicles to perform coordinated actions to meet certain ethical criteria. This comprises the novel concept of ethical V2X. In fact, V2X is to be considered as the only possible way to coordinate the actions of autonomous vehicles to address certain ethical challenges.

Paper V demonstrates the envisioned concept of ethical V2X through an example of longitudinal driving of a three-vehicle formation. To quantify the severity of an imminent collision, the notion of harm is used. The harm is calculated by considering the velocities at the moment of impact and the masses of the colliding vehicles. Ethical requirements are embedded into the calculation of the harm by assigning respective "priority" coefficients to each involved vehicle. Considering emergency braking for a three-vehicle formation, Paper V presents an algorithm for calculating harm and shows how the value of harm is dependent on the braking deceleration value or magnitude  $a_2$  applied by the middle vehicle. In some cases, it is even possible to choose deceleration magnitude  $a_2$  such that the harm (total or individual for a particular vehicle) becomes zero. It implies that with a proper choice of braking strategy (value  $a_2$ ),

which is enabled by the adoption of the ethical V2X concept, certain collisions can be prevented. Hence, when referring to imminent collisions, we indicate those that cannot be prevented without cooperation between vehicles. When collision avoidance through vehicle cooperation becomes unfeasible, we refer to unavoidable collisions. The ethical V2X framework extends beyond merely addressing how to prevent imminent collisions. In scenarios where, even with vehicle cooperation, collisions become unavoidable, the outcome of such collisions might still be mitigated or redistributed based on ethical considerations. This becomes possible by the use of the ethical V2X framework.

Paper VI extends the framework of ethical cooperation and discusses ethical dilemmas for autonomous driving at a higher level. The ethical cooperation between vehicles results in an *ethical* strategy, which is compared to a *normal* strategy where vehicles perform evasive maneuvers without agreeing with others. Here, risk calculation is used for a comparative analysis between normal and ethical braking. The risk is formally defined as the expected value of harm, which involves the multiplication of harm by its associated probability and subsequent summation across all possible outcomes. The main source of the stochastic nature of the harm is unreliable inter-vehicular radio communications. The main idea behind choosing the appropriate ethical strategy is addressing the potential failure of its execution due to unreliable V2X communication in order not to exacerbate the harm resulting from normal strategy. In other words, the choice of ethical strategy should not worsen the situation compared to the normal case when vehicles do not cooperate. The proposed methodology is illustrated by the case study of emergency braking with three vehicles in longitudinal driving. Several simulation examples are presented that show that the proper choice of deceleration value  $a_2$  leads to a risk reduction. Additionally, the probability that harm does not exceed a predefined threshold is presented as an extra metric for the further evaluation of the ethical protocol. The use of this metric is illustrated in the same case study.

## 1.5 Thesis Structure

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

## 2. Background and Related Works

### 2.1 RSS Model and Other Approaches to Safety of Autonomous Vehicles

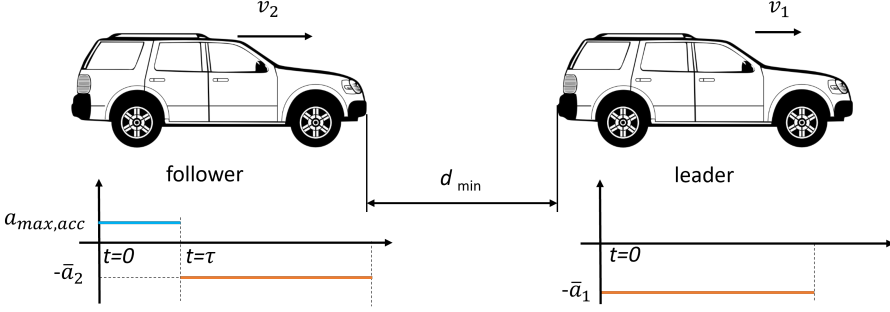
There are different approaches regarding the definition of safety for AVs. One of the useful approaches is to generate complete and well-defined driving rules an AV could follow to ensure safety on the roads. The RSS model [19] formulates a set of rules that prioritize safety and scalability, asserting that any vehicle adhering to this model is not responsible for causing an accident.

RSS provides formal, rigorous guarantees for safety, presenting a deterministic envelope within which AV can operate safely. Among the rules of the RSS model is mathematically expressed safe longitudinal distance that should not be violated to not hit someone from behind. Such a safe distance between two vehicles, referred to here as the leader and the follower, is defined with respect to the velocities of both vehicles, the response time  $\tau$  of the follower, and some additional parameters. For two vehicles driving in the same direction along a straight road, the minimum longitudinal safe distance  $d_{min}$  is given by [19]:

$$d_{min} = [v_2\tau + \frac{1}{2}a_{max,acc}\tau^2 + \frac{(v_2 + \tau a_{max,acc})^2}{2\bar{a}_2} - \frac{v_1^2}{2\bar{a}_1}]_+ \quad (2.1)$$

where  $[x]_+ := \max\{x, 0\}$ ,  $v_1$  is the initial velocity of the leader,  $v_2$  is the initial velocity of the follower,  $\tau$  is the response time of the follower,  $\bar{a}_1$  is the maximum deceleration value applied by the leader during braking,  $\bar{a}_2$  is the minimum (reasonable) deceleration value applied by the follower during braking, and  $a_{max,acc}$  is the maximum acceleration applied by the follower during the response time. For clarity, the assumed acceleration/deceleration profiles of the two vehicles are illustrated in Fig. 2.1.

The RSS model has a transparent and open white-box nature, presenting an interpretable and formal framework. It has become the backbone of the driving policy of Mobileye [20], a globally recognized company whose technologies are deployed in over 65 million vehicles [21]. Intel, the parent company of



**Figure 2.1:** Schematic scenario of RSS model showing acceleration/deceleration profiles of the involved vehicles.

Mobileye, is actively collaborating with industry stakeholders, governments, and regulatory bodies to promote RSS as a global standard for AV safety. The real-world applicability and effectiveness of RSS have been demonstrated in Intel’s AV development fleet [22]. Furthermore, Mobileye recently proposed a novel collision-preventing system based on a generalization of the RSS [23]. In [24], the RSS serves as a central component in many safety architectures for automated driving, forming an integral part of a layered simplex architecture. Thus, the RSS model is gaining recognition and support as a viable framework for ensuring AV safety.

Limitations of the RSS model have been investigated and reported in [25–29]. Specifically, due to the improper choice of model parameters, the minimum distance provided by the RSS can become unnecessarily large, which has a negative effect on road efficiency [27]. An attempt to optimize parameters of the RSS model is made in [27] to achieve a trade-off between safety and efficiency. The proposed models are assessed by numerical simulations. Several studies [25; 27; 28] suggest the RSS parameters calibration based on naturalistic driving data, typically with a focus on specific scenarios such as cut-ins, near-crashes, or all safety-critical events.

A special case, namely when  $\bar{a}_1 < \bar{a}_2$ , where safety cannot be guaranteed by the original RSS formulas, has been reported in [29]. However, the exact parameter domain for this special case is not fully described and lacks one condition. Without this condition, the safe IVD becomes unnecessarily large. The results presented in this thesis fill this gap. Furthermore, the thesis generalizes the RSS model by extending the worst-case assumption on the follower’s controller (maximum constant acceleration) to an arbitrary acceleration/deceleration profile. Such an improvement allows to decrease RSS distances at the expense of requiring additional knowledge about the controller of

the follower. A similar attempt is made in [23] in order to integrate the RSS in a collision avoidance system. However, [23] covers only a specific class of braking profiles (jerk-bounded profiles), while the results presented in this thesis are more general.

Below, we mention a number of other approaches to the safety of automated or fully autonomous driving. Safety Force Field (SFF) [30], released by NVIDIA, is a mathematical model to guarantee safety for AV by trying to avoid unsafe situations. SFF is based on the measure for the intersection of trajectories. It is a computational mechanism that defines constraints on control that, if obeyed, prevents all collisions. The safety force field is defined in such a way that if actors obey the constraints, they avoid unsafe states, thereby preventing collisions.

Reachability analysis can be used for runtime verification of the safety of trajectories in arbitrary traffic situations [31; 32]. Safety can be ensured with respect to modeled uncertainties and behavior as long as the presence of the automated vehicle does not interfere with the presence of other road users at any point in time [31]. In general, applying reachability analysis in analyzing the safety properties of automated driving is computationally intensive and requires strict assumptions as well as various approximations, even in simple scenarios [33]. In [34], reachability analysis is combined with convex optimization to define fail-safe trajectories within dynamic driving corridors. However, the prediction only considers behavior that does not violate a set of formalized traffic rules.

An approach for addressing safety of automated driving is to identify traffic conflicts by measuring the risk associated with collision proximity. For this purpose, time-based metrics such as TTC (see Sec. 2.4) and a few more complicated ones based on TTC are used. Other proposed measures include deceleration-based and energy-based metrics [35]. Generally, all those metrics rely on certain thresholds to identify risky interactions associated with crashes. These metrics have the potential to be employed for fully autonomous driving if appropriately revised, for example, by adjusting their thresholds [35].

Data-driven approaches, an alternative to rule- and logic-based models, suffer from weak generalization and scalability. This implies that they struggle to properly handle rare edge cases and diverse scenarios that might occur in real-world driving situations [36; 37]. Additionally, data-driven algorithms are often viewed as black boxes, making it difficult to provide human-understandable explanations for their decisions [19]. This limits the potential for further optimization of the system. Furthermore, achieving an acceptable level of safety with a statistical data-driven approach is considerably challenging due to the vast amount of required data (collected mileage) and the inability to validate a multi-agent system offline.

## 2.2 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 [38].

Platooning saves road space due to small IVDs, and thus increases the efficiency on the roads. Furthermore, as demonstrated in numerous experiments [5; 16; 17; 39], platooning decreases fuel consumption for heavy-duty vehicles due to decreased air drag force. In [39], 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 fuel if it follows another one in a platooning formation. The recent literature overview [5] 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 [5].

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 [40].

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 [40]. Platooning control strategies and related spacing policies that ensure string stability were addressed in many early works on string-stability [41–43]. 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 [44]. 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 [45], 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 [46; 47]. In [48; 49], 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 [50]. 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 [51]. 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 [52], 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 2.4.

## 2.3 Vehicle Communication

The current paradigm of the self-driving car manufacturers on enabling fully autonomous vehicles is mainly based on 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 [53–55]. 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 [56; 57]. 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 [58]. 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 [59; 60] 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 Communication (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 [61]. It includes such C-ITS applications as stationary vehicle warning, Emergency Electronic Brake Lights (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 [62]. 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 [63]. Low-frequency container of CAM contains essential static information about the vehicle, such as the vehicle's identification, vehicle type, dimensions, and other characteristics that do not frequently change. The high-frequency container of CAM usually contains dynamic information, such as speed, heading, position, and other rapidly changing parameters. 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 developed within the European research project ENSEMBLE [64]. 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 [65]. 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 vehicle communication to form a platoon, the structure of messages required for driving in a platoon, joining, and leaving the platoon.

For effective and safe platooning control, Ultra-Reliable Low Latency Communication (URLLC) becomes vital, especially in high-speed scenarios [60]. The V2V transmissions undergo channel impairments causing packet 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  $p_i$ ).

## 2.4 Emergency Braking

Modern vehicles are often equipped with ADAS [66], helping a driver in regular (e.g., ACC, line keeping assistant, blind spot detection, etc.) and critical traffic conditions (e.g., AEBS [67], Collision Avoidance Systems [23], 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 a 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 signals. Even slight braking can be automatically applied to draw the driver's attention. "Emergency braking phase" is automatically initiated if the driver does not respond to warnings.

In AEBS, metrics such as TTC are often used for triggering "warning" and "emergency braking." TTC is defined as the remaining time before a rear-end collision happens if the speed and course of the involved vehicles remain constant. Selection of a higher TTC-threshold implies greater safety at the expense of a larger number of false positive brakes and an increased level of nuisance for the driver. Selection of a lower threshold implies less safety; thus, it might not be enough to prevent rear-end collisions, especially at high velocities. According to European regulations on advanced emergency braking systems [68], no emergency braking should start "before TTC equals to or less than 3 s." For some systems [69], as well as for non-assisted drivers [70], this threshold on a hard braking initializing can be even lower than 2 s. While this trade-off threshold helps prevent collisions at low speeds, it only somewhat mitigates collisions at higher speeds, which, in turn, are still lower than highway driving speeds [23].

A novel preventive system based on RSS was proposed by Mobileye recently [23]. To provide collision prevention, a constant decelerating profile in the original RSS model is replaced by a jerk-bounded profile. This modification allows the system to operate with relatively large TTC while supporting smooth braking. The proposed Automatic Preventive Braking (APB) system offers proactive and milder interventions to driving for enhanced safety. Following the RSS framework, the APB system will start to brake with a pre-defined jerk until either the car stops or the distance to the preceding vehicle becomes safe again. According to the vision in [23], if all road users comply with the proposed system, then collision rates will drop considerably below current AEBS rates. [71] suggests an improvement of the proposed APB by introducing a response time, safety buffer, and a minimum following distance to the generalized RSS formulas. Whereas virtual tests show that the improved system performs better than APB in safety-critical events, there are no inves-

tigations of normal car-following scenarios where braking interventions could be considered false positives.

Introduction of V2X communications enables improvements of onboard sensor-based ADAS to various C-ITS applications. For example, with EEBL [72; 73], 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 V2X communication channel – the higher the packet error rate, the more DENMs repetitions are needed to inform other vehicles about the critical situation.

Different metrics can be used to assess safety in 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 TTC (TET) and Time Integrated TTC (TIT), are proposed in [74]. These 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 [7] to quantify the potential of rear-end collisions. The proposed methodology is based on inductive loop detector data and enables the identification of collision potentials in real time. Based on information theory approaches, some common properties for metrics of functional safety are listed in [75]. In [76], continuous future risk function over time is introduced. It can be used for risk estimation, 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 [39] by calculating the overall stopping distance of a platoon leader and followers using Monte Carlo simulations. In [77], various Monte Carlo simulations are carried out for different values of traffic speeds and pavement conditions to calculate the probability of multi-vehicle collision. Probabilistic distributions for reaction time, tire performance, braking deceleration, and vehicle time gaps are considered. In [78], 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 time-critical applications. Related simulation results for emergency braking are presented in [79].

To guarantee safety in emergency braking scenarios, several braking strategies are proposed in the literature. An emergency braking strategy is presented in [80], 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 braking protocol in [81], 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 [82], platooning vehicles are required to be sorted in the order of increasing stopping distances. In [83], 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.

The safety of the vehicular following scenario is analyzed in [84]. The paper proposes a collision avoidance strategy for a mixed traffic scenario, wherein an autonomous vehicle is approaching a potential obstacle and is followed by a conventionally manually driven vehicle. In this strategy, the autonomous vehicle takes into consideration the anticipated braking of the following conventional vehicle and adapts its deceleration to avoid both front-end and rear-end collisions.

The 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 III and IV.

## 2.5 Ethical Decision-Making

Autonomous driving holds the promise to ensure safe future mobility. Autonomous decision-making may properly manage road situations where humans make errors. Still, there will be situations where accidents are challenging or even impossible to prevent [10; 11].

Such situations may arise due to limitations of vehicular automation, for example, insufficient sensing capabilities [12]. Another source that contributes to the occurrence of such scenarios is unsafe human behavior, for example, hazardous driving styles exhibited by human drivers (in mixed traffic conditions) or spontaneous actions of cyclists or pedestrians [13; 14]. These edge cases are considered very unlikely but yet present, and autonomous vehicles must know how to respond to them. As generally agreed upon, this response should align with ethical principles [10].

The first deliberations on the ethical aspects of autonomous vehicles arose as hypothetical discussions about various potential scenarios. However, with

the first experimental self-driving cars appearing on the road and the first accidents involving them, those discussions evolved from purely theoretical considerations into real-world challenges [85]. Since then, the ethics of self-driving cars have become a hot topic of debate.

One of the most debated questions revolves around how AVs should be programmed to respond to accident scenarios. To address this, we first need to determine the pre-set priorities for self-driving vehicles. For instance, one ethical consideration may involve prioritizing the minimization of *harm*, where the algorithm aims to reduce the number and severity of potential injuries (or fatalities) in the event of an unavoidable collision. In this context, the term "harm" broadly refers to the overall severity of an accident. One obvious factor determining the severity of an accident is the number of people expected to be injured. Other measurable values, such as masses and velocities at the impact of the involved vehicles, play a significant role in determining harm. Furthermore, details such as the vulnerability level of those involved (considering factors like age, state of health, whether they are passengers or pedestrians, whether passengers are wearing seat belts, etc.) can also be taken into consideration [13; 85]. However, in addition to minimizing overall harm, another ethical consideration is the overall fairness of the accident's outcome, that is, how harm is distributed among the involved actors. Despite numerous discussions and the active involvement of the research society and various stakeholders, there is still no clear answer on how to determine the "*importance*" (or "*priorities*") of different road users in an accident scenario. Nevertheless, it is universally agreed that the resolution of ethical dilemmas is crucial for gaining public trust and the widespread adoption of autonomous vehicles.

A significant role in the development of AVs' ethical decision-making plays risk ethics [86]. In general, this involves quantifying the consequences of a potential collision and assessing the probability of such an outcome. The stochasticity in the risk assessment can encompass factors such as the unpredictability of other actors' behavior, uncertainties in vehicle control, and the knowledge of parameters related to other actors with some level of uncertainty [87].

Recently, a number of algorithms for ethical trajectory planning have been introduced, guided by risk ethics. In [87], an ethical path-planning algorithm for accident-related scenarios is developed which allows for a fair distribution of risks. It involves sampling potential trajectories and calculating associated risk values for every road user in each trajectory. These sampled trajectories are then classified into four validity levels. Trajectories exceeding the maximum acceptable risk are declared "invalid". For "valid" trajectories, an ethical cost function is calculated. This function takes into account the minimization of overall risk, priority for the worst-off, equal treatment of all human road

users, and responsibility considerations. Finally, the trajectory with the highest level of validity and the lowest estimated cost is selected for execution [87].

In [11], a strategy for autonomous decision-making, an Ethical Valence Theory, is presented. In this framework, every road user is assigned an ethical valence, determined by a socially acceptable classification or hierarchy (e.g., pedestrians have higher valence than vehicle passengers). For every possible action of the AV, harm is defined by the difference of velocities between the two implicated road users and the structural vulnerability coefficient. Subsequently, the expected harm is calculated by using transition probabilities that represent the estimation uncertainty about the behavior of other road users. The final choice of action depends on the optimization procedure based on the chosen moral profile. The proposed approaches include risk-averse altruism (aiming to minimize the expected harm of the road user with the highest valence until the ego vehicle's collision becomes severe) and threshold egoism (aiming to minimize the expected harm of the AV until the risk to a road user with a higher valence becomes severe).

Model Predictive Controller based on Lexicographic Optimization is designed for ethical decision-making in [88]. In the first step, the controller collects information about obstacles and the environment, as well as identifies the possible action field. The severity of potential collisions with all existing obstacles (pedestrians, cyclists, vehicles) is then calculated, which determines the priority of each obstacle. Based on information from the potential field, obstacle priorities, and additional constraints, the autonomous vehicle chooses the best action. A multi-layer route selection strategy with ethical considerations is proposed in [89] for automated vehicles under critical situations. The presented method is based on a graph-based route selection algorithm. For every possible route, the probability of collision is estimated. Additionally, the risk of an accident with serious injuries or fatalities is assessed through the velocity of the automated vehicle and the surrounding vehicles, pedestrians, etc. Finally, the algorithm chooses the route that guarantees the minimum probability of a critical conflict on the graph.

According to the current state of knowledge, there are no formalized methodologies for solving ethical dilemmas for autonomous vehicles in a cooperative approach, wherein vehicles collectively agree on certain actions to optimize the outcome of an accident. Thus, Papers V and VI represent a first step in this direction, where V2X communication plays a key role in the ethical resolution of multi-vehicle accident scenarios.

### 3. Summary of Appended Papers

This chapter provides a summary of the appended papers. Papers I-IV provide safety analysis for longitudinal driving involving vehicles driving in a platoon or following each other, whereas Papers V and VI investigate how to minimize the consequences of unavoidable accidents when safety guarantees are not ensured.

#### 3.1 Paper I

Paper I is the first in a series of papers providing a safety analysis for longitudinal driving, and it presents a general safety framework. We consider two vehicles, referred to as the leader and the follower, moving along a road with a short IVD. At some point in time, the leader abruptly emergency brakes with its maximum braking value  $\bar{a}_1$  (e.g., due to a pedestrian appearing on the road), and the follower has to brake in response to avoid a rear-end collision. During a response time  $\tau$ , the follower keeps moving using its normal control policy. The response time  $\tau$  may capture various types of delays, including perception delays, communication delays (in case V2X employed), as well as delays associated with decision-making, computing systems, and architecture design. Once the time  $\tau$  has elapsed since the leader initiated emergency braking, the decision of emergency braking is made by the follower, and it applies its maximum possible deceleration value  $\bar{a}_2$ . The explicit decision-making algorithm is out of focus in this paper. Note that values  $\bar{a}_1$ ,  $\bar{a}_2$  are positive and represent deceleration values applied by respective vehicles at braking. Throughout the thesis, we may occasionally omit wordy expressions such as "value" or "magnitude" even though they are implied. In such cases, it should not be misinterpreted as implying that  $\bar{a}_1$  or  $\bar{a}_2$  is negative.

To find the minimum safe distance ensuring collision-free behavior, we introduce a computationally efficient three-step methodology:

- In the first step, we introduce the novel concept of "minimum safe braking set". It comprises a two-dimensional hyper-surface in a three - dimensional space of kinematic variables. If the dynamic parameters of the vehicles attain values in this set, the follower vehicle has to initiate

emergency braking immediately to avoid a rear-end collision. We use this set to impose constraints on vehicles' trajectories.

- In the second step, the explicit solution of trajectories for two vehicles on the interval  $[0, \tau]$  is derived. Without loss of generality, we assume that the leader initiates emergency braking at time zero.
- Finally, the third step combines the computed expressions from the two steps above. It yields an analytical expression of IVD such that when the follower uses the controller for  $\tau$  seconds, the kinematic variables exactly reach the "minimum safe braking set" derived in the first step.

Utilizing this methodology, first, we derive minimum safe IVDs for the setting considered in the RSS model. The RSS model assumes a "worst case scenario" where the follower accelerates at a constant rate during its response time interval until switching to emergency braking at the time  $\tau$  by applying its maximum possible deceleration value  $\bar{a}_2$ . We show that RSS-based IVDs are insufficient and lead to collisions when the follower has a higher decelerating capacity than the leader, i.e., when  $\bar{a}_2 > \bar{a}_1$ . We fill this gap and provide an extra mathematical formula covering this case. In this sense, we complete the RSS model for longitudinal driving by presenting a comprehensive expression for minimum safe IVD and the explicit conditions under which this expression is applicable.

Second, we generalize the RSS model for longitudinal driving by replacing the conservative assumptions of constant acceleration with an arbitrary acceleration/deceleration profile, denoted as  $h(t)$ . This function describes the evolution of the follower's acceleration and deceleration during the response time interval. Such a function covers a state-dependent feedback controller under the assumption that the closed-loop dynamics are solvable, thereby allowing its representation as a function of time. Considering an arbitrary function implies that, instead of assuming that the follower applies constant acceleration during the response time interval, we derive minimum safe IVDs under more realistic assumptions. Knowledge of the follower's profile, such as acceleration/deceleration and jerk intervals, allows to obtain smaller safe IVDs compared to the conservative bounds obtained via RSS.

Furthermore, we prove that for some function  $g(t)$  bounding  $h(t)$  from above, the methodology yields distances with higher safety guarantees compared to those corresponding to the actual acceleration/deceleration profile. A tighter bounding function results in shorter IVD. Substituting the real acceleration/deceleration profile  $h(t)$  with a computationally more tractable function  $g(t)$  increases the required minimum safe distance but facilitates easier derivations. Several examples are presented in the paper to illustrate how different bounding functions affect the resulting minimum distances.

### 3.2 Paper II

Paper II presents an example of how the three-step methodology can be applied to the case when vehicles use ACC along with additional V2X communication. Two operation modes for vehicles are considered: *normal* and *emergency braking*. In the *normal* mode, the follower uses ACC with a constant-distance policy to follow the leader with a short desirable IVD. 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 its maximum deceleration until standstill. Simultaneously with braking, the leader starts repeatedly transmitting EMs to the follower over the dedicated communication channel using V2V communication. The EM informs the involved vehicle about the emergency braking situation, i.e., implicitly asking the receiving vehicle to enter the *emergency braking mode*. The follower resides in the normal mode and uses an ACC controller until the EM is received, i.e., during some communication delay  $\tau^*$ . After that, it enters emergency braking mode by applying its maximum possible deceleration. In such a setting, the response time of the follower considered in Paper I represents a communication delay in Paper II.

Using the same three-step methodology, Paper II derives minimum safe IVD as a function of communication delay. Analytically obtained dependence of IVD on communication delay  $\tau^*$  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 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, the safety metric, namely the probability of no collisions, is computed in the paper. Naturally, an increase in IVD increases the probability of safe braking (i.e., no collisions).

### 3.3 Paper III

Paper III extends safety analysis to encompass  $N$  consecutive vehicles moving in a platoon formation. However, compared to Papers I and II, here, an open-loop configuration is under consideration. In other words, followers are assumed to travel with a constant velocity until emergency braking. The paper investigates how V2V communication can be used to reduce inter-vehicle distances between platooning vehicles 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, as in Paper II, 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. The *emergency braking mode* is initiated by the received EM, transmitted by the leader. Reception of the EM by the  $i$ -th vehicle depends on communication channel quality, which is defined by a packet loss probability  $p_i$ .

Paper III focuses on finding optimal IVDs that minimize the fuel consumption of the platoon moving in *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 [39]. 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 the 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 dependent on the braking capabilities of vehicles, velocity, and communication quality. 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 to 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 to the optimization problem. In this case, relevant data from all platoon members for deciding upon appropriate IVDs for all vehicles should be gathered centrally, e.g., by the platoon leader. Temporally reduced braking capabilities of the vehicles in the platoon allow for decreased inter-vehicle distances, which leads to better fuel economy and road space utilization.

To summarize, the centralized approach allows for global optimality, while

the decentralized one 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 against a more relaxed communication setting. The usefulness of the presented approaches is illustrated through several computational simulations.

### 3.4 Paper IV

In Paper IV, we compare how safe emergency braking can be handled by V2V communication on the one hand and by radar-based AEBS 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 emergency braking and the necessity to stop in order to avoid rear-end collisions. In the second one, it is assumed that the platoon does not utilize V2V communication. Instead, all vehicles rely on 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 TTC-thresholds  $T_{AEBS}$  have to be chosen for practical applications.

For both setups, metrics characterizing the likelihood of a crash are derived. They link platooning operation to the safety requirements. Through the introduced metrics, safety in platooning operation can be assessed directly. Those metrics define the maximum time delay for the vehicle to switch to full braking to avoid a rear-end collision with the preceding vehicle. In the terminology used in Paper I, this corresponds to the maximum allowed response time given the fixed IVD. Having the desired level of safety, i.e., the desired value of safety metric, Paper IV explicitly obtains minimum safe IVDs. These IVDs allow avoiding rear-end collisions with a given probability.

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 qualities of the wireless channel (through packet loss probabilities  $p_i$ ) are 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). Conversely, mainly for low velocities, AEBS solution allows for shorter IVDs in conditions with a poor V2V communication quality. It is worth mentioning that if TTC does not reach the threshold  $T_{AEBS}$  during the

maximum allowed time delay (which is typical for high velocities as demonstrated by the presented results), 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.

### 3.5 Paper V

Paper V focuses on resolving ethical dilemmas in multi-vehicle scenarios. The specific problem addressed considers the longitudinal driving of three autonomous vehicles. Similar to papers I-IV, we focus on the emergency braking scenario. The three vehicles driving after each other on the road are referred to as Vehicle 1, Vehicle 2, and Vehicle 3, respectively. At some point in time  $\tau_1$ , Vehicle 1 starts emergency braking. In response, Vehicles 2 and 3 start braking at some times  $\tau_2$  and  $\tau_3$ , respectively. We assume that at emergency braking, Vehicle 1 and 3 apply their maximum possible deceleration values  $\bar{a}_1$  and  $\bar{a}_3$ , respectively. The primary focus is on designing the behavior of Vehicle 2, which does not necessarily have to perform maximum braking with  $\bar{a}_2$ , but can instead select some reduced deceleration value  $a_2^* \leq \bar{a}_2$ . If it is possible to avoid all collisions by choosing an appropriate  $a_2^*$ , that should be the preferred course of action. However, if collisions between the considered vehicles are unavoidable (due to too short IVDs), the objective is to minimize the accident's severity.

To quantify the severity of a collision, the notion of harm is used. The harm is calculated by considering the velocities at the moment of impact and the masses of the colliding vehicles. Ethical requirements are embedded into the calculation of harm by assigning respective "priority" coefficients to each involved vehicle. The ethical reasoning behind resolving a specific dilemma is beyond the scope of this study. Instead, we provide means for deciding how an unavoidable crash can occur in order to meet formalized ethical requirements.

Considering emergency braking for a three-vehicle formation, Paper V presents a computationally efficient algorithm for calculating harm and shows how the value of harm is dependent on the braking deceleration  $a_2^*$  applied by Vehicle 2. The algorithm is built upon analytically derived formulas presented in the paper. These formulas define the moments of collision of vehicles and their velocities at these moments.

The numerical simulations in the paper illustrate how the presented approach serves as guidance for choosing braking deceleration  $a_2^*$ . The results demonstrate that, in certain cases, it is even possible to choose deceleration  $a_2^*$  such that harm (total or individual for a particular vehicle) reduces to 0. In the other presented cases, regardless of the chosen deceleration rate, there

always occurs at least one collision among the three considered vehicles. The harm graph produced by the algorithm shows how the order of pairwise collisions changes with varying  $a_2^*$ , consequently influencing the harm values. As demonstrated by the examples, the proper choice of  $a_2^*$  has the potential to reduce harm for all vehicles involved in the emergency braking scenario. We emphasize that this is only possible if autonomous vehicles cooperate with each other. The reason for this is that the second vehicle needs to know the parameters of the first and the third vehicles in order to execute the algorithm and estimate the harm function. These parameters, both static and dynamic, can be transmitted via V2X using heartbeats. Additionally, certain parameters, such as the time of braking for Vehicle 1, i.e.,  $\tau_1$ , can be included in EMs transmitted by Vehicle 1 at the onset of braking.

### 3.6 Paper VI

Paper VI explores ethical dilemmas in multi-vehicle scenarios in a broad sense. Despite technological advancements, accidents will continue to occur, with collisions being a likely consequence. Although these corner cases are very unlikely, they must be addressed by the autonomous vehicles' motion planning logic, ensuring adherence to ethical principles. In this context, V2X is seen as an essential means that enables AVs to perform coordinated actions to meet certain ethical criteria.

The ethical cooperation between vehicles results in an *ethical* strategy, which is compared with a *normal* strategy when vehicles perform evasive maneuvers without agreeing with others. The ethical approach, in general, requires an exchange of information between the involved vehicles. The essential requirement for choosing the appropriate ethical strategy is addressing the potential failure of execution due to unreliable V2X. In other words, the choice of ethical strategy should not worsen the outcomes of the accident compared to the normal case where vehicles do not cooperate.

To formalize this requirement, a notion of risk  $R$  is introduced. The risk is formally defined as the expected value of harm, which involves the multiplication of harm by its associated probability and subsequent summation across all possible outcomes. Within Paper VI, the main source of the stochastic nature of the harm is unreliable inter-vehicular wireless communication. The requirement for designing an ethical inter-vehicular interaction protocol, as mentioned above, is formulated as  $R_n \geq R_e$ , where  $R_n$  is the risk for the normal maneuvering and  $R_e$  is the risk for the ethical cooperative resolution.

The proposed methodology is illustrated by a case study of emergency braking for three vehicles in a longitudinal driving scenario. It is the same scenario as considered in Paper V, where the three consecutive vehicles are re-

ferred to as Vehicle 1, Vehicle 2, and Vehicle 3. The normal strategy assumes that Vehicles 2 and 3 start emergency braking once they receive the EM from Vehicle 1, at times  $t_2$  and  $t_3$ , respectively. Additionally, it assumes that Vehicle 2 applies its maximum deceleration magnitude  $\bar{a}_2$ . In the ethical strategy, Vehicles 2 and 3 delay the initiation of emergency braking until pre-agreed time instances  $\tau_2$  and  $\tau_3$ , respectively, and Vehicle 2 furthermore chooses deceleration with magnitude  $a_{2,e} \leq \bar{a}_2$ . The value of  $a_{2,e}$  (denoted as  $a_2^*$  in Paper V) is chosen by Vehicle 2 in order to meet ethical criteria, namely, to reduce or redistribute potential harm for the involved actors. Ethical considerations, like in Paper V, are integrated into the calculation of risk by assigning individual "priority" coefficients to each involved vehicle. Obviously, the ethical strategy can be executed only if  $t_2 \leq \tau_2$  and  $t_3 \leq \tau_3$ . If, due to unreliable communication,  $t_2 > \tau_2$ , then Vehicle 2 falls back to normal braking strategy by initiating braking at  $t_2$  with its maximum deceleration value  $\bar{a}_2$ . If  $t_3 > \tau_3$ , then Vehicle 3 initiates braking later than prescribed by the ethical strategy. Although even if in such cases, having  $t_2 \leq \tau_2$ , Vehicle 2 independently initiates braking at  $\tau_2$  with the chosen  $a_{2,e}$ , the ethical strategy is still regarded as unexecuted. Taking into account the probability of packet loss between the vehicles, Paper VI provides analytical formulas to calculate the risk for both normal and ethical strategies. Furthermore, the risk calculation for ethical strategy considers its probable failure as described above.

Several simulation examples using a range of varied parameters (deceleration capabilities, initial velocities of the vehicles, pre-agreed time instances  $\tau_2$  and  $\tau_3$ ) are presented in the paper. These examples demonstrate that the proper choice of  $a_{2,e}$  leads to a risk reduction. Additionally, the probability that harm does not exceed a predefined threshold is calculated as an extra metric for further evaluation of the ethical protocol.

## 4. Conclusions and Future Work

### 4.1 Conclusions

This thesis addresses safety and ethical decision-making in cooperative automated driving. New results and theory are presented along two interconnected lines of research. Firstly, we present analytic and efficiently computable guarantees for safe automated driving in vehicle platooning or following. Secondly, we present an ethical V2X framework designed for resolving ethical dilemmas encountered in multi-vehicle scenarios. The former research direction intersects the latter in scenarios where imminent collisions need to be addressed.

In the first line of results, we provide computationally efficient methods and algorithms for the calculation of minimum inter-vehicle distances, guaranteeing no rear-end collisions in strings of vehicles. These IVDs are theoretically obtained for closed-loop (Papers I and II) and open-loop (Papers III and IV) configurations. In the former, specifically in Paper I, safety guarantees are obtained for an arbitrary time-dependent function representing the acceleration/deceleration profile of a vehicle. Such a function represents a vehicle's control policy if the dynamics of the system can be explicitly solved. If this function is constrained by some bounding function, then the computed distances corresponding to the bounding function provide the same safety guarantees at the expense of longer required IVDs. The closer the bounding function is to the real acceleration/deceleration profile, the shorter the minimum safe distances can be obtained. The worst-case consideration, when the bounding function is set as a maximum constant acceleration, results in the well-known RSS formulas for safe longitudinal driving. However, the formulas presented in this thesis represent an enhanced version of the original RSS distances. The improvement lies in providing full comprehensive formulas where any possible deceleration capacities of the involved vehicles are considered.

The safety guarantees in Paper I represent a general result, not only due to their derivation under the assumption of an arbitrary acceleration/deceleration profile, but also because they are dependent on the arbitrary response time of a vehicle. Such a time can constitute a response time of onboard sensors or a communication delay if V2X communication is employed. The safe IVDs derived in Papers II-IV explicitly depend on the V2V connectiv-

ity quality expressed by packet loss probabilities. Degraded performance of wireless communication links, i.e., when many repetitions of messages are required to successfully deliver information about emergency braking, 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 IV. The results show that the proposed solution based on V2V connectivity outperforms the AEBS approach in terms of minimum allowed IVDs even for relatively poor communication quality. This is especially observable for high vehicular velocities.

The methodology provided in this thesis allows obtaining safety guaranteeing conditions not only in the spatial domain, i.e., as IVDs, but also in the temporal domain. This is manifested in the computable maximum communication delay (or response time). Hence, this thesis provides results that can be used to develop control and communication policies for cooperative automated driving applications.

Although edge cases resulting in collisions for autonomous vehicles are considered very unlikely, they must still be addressed by the autonomous vehicles' motion planning logic, with decisions adhering to ethical principles. Adhering to ethical principles in the development and deployment of AVs is essential for promoting public understanding and acceptance. The thesis presents a framework of ethical V2X, where V2X is acknowledged as an essential means enabling autonomous vehicles to perform coordinated actions to meet certain ethical criteria. The presented framework demonstrates how the risk or harm resulting from unavoidable collisions can be mitigated or redistributed under ethical considerations through cooperation between vehicles.

To summarize, the thesis offers approaches to guarantee safety and incorporate ethical considerations into decision-making within automated driving systems. Overall, the presented results show the important role of V2X communication for improved safety in critical traffic scenarios where onboard sensors might not respond fast enough to prevent serious consequences. Moreover, admitting that not all accidents can be prevented by AVs, the thesis proposes a framework for mitigating the severity of unavoidable collisions through cooperative maneuvers. This highlights the importance of V2X communication both in preventing collisions and in mitigating accident severity in an ethical way if, for any reason, the required safe guarantees were not maintained. Furthermore, the results of the thesis, obtained through analytical approaches, offer a human-understandable logic and white-box nature, which should contribute to the widespread adoption of autonomous vehicles and facilitate their integration into society.

## 4.2 Future Work Directions

There are several promising directions for extending and expanding the results presented in this thesis. One of such future work directions is to consider more advanced vehicle dynamics and environment models. With more realistic modeling, one can expect to obtain more accurate bounds on spacing policies, as well as improved precision in calculating harm values in the event of a vehicle collision. More precisely, the following options can be considered:

- Incorporating more realistic dynamics models of vehicles, e.g., time-varying decelerations for all involved vehicles;
- Incorporating more realistic environment models, e.g., time-varying road slopes, curves, weather-dependent road friction;
- Considering more realistic sensor models where error measurements are taken into account;
- Incorporating a higher degree of realism into the modeling of vehicle collisions, e.g., accounting for the angle of impact, detailed vehicle shape.

Another interesting line of research to pursue is to add more physical details of signal 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 [90; 91], stochastic [92; 93], and hybrid geometry-based stochastic channel models [94]. Especially promising in this context are simulators built upon the latter models, wherein packet loss probabilities can be measured in various scenarios [95; 96].

In this thesis, the focus has been on the IEEE 802.11p protocol, although our results are applicable to a wider scope of communication technologies. Having IEEE 802.11p as a standard for V2X, communication quality represented via  $p_i$  primarily depends on two factors: deterioration of signals due to the channel propagation and interference caused by packet collisions from communicating nodes. Extending this work to C-V2X holds promise since the dedicated scheduler can effectively utilize radio resources, potentially lowering the probability of packet collisions and communication latency. This makes C-V2X more perspective for handling time-critical applications. In C-V2X, the modeling 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.

Presented in the thesis, the framework of ethical V2X (and V2V as a special case) is a first step towards formalizing the use of V2X for resolving ethical

dilemmas in imminent conflicts. The thesis demonstrates that cooperation between autonomous vehicles holds great potential in reducing the severity of accidents. As mentioned above, more advanced modeling can improve the accuracy of calculating harm values at collisions. Furthermore, to refine risk calculation, additional sources of uncertainty beyond unreliable V2X communication can be considered, such as those arising from sensing and actuation in autonomous driving.

Furthermore, the results obtained for a two-vehicle case have the potential to be generalized for strings consisting of an arbitrary number of vehicles, for example, by treating it as a cascade system and applying methods such as backstepping [97; 98]. The safety analysis can be done in the space or time domain, where the latter implies the usage of the maximum allowed response time or communication delay. Furthermore, communication delays can be replaced by a more general approach, which takes the Age of Information (AoI) into account [99]. 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 [100].

Regardless of the V2X communication technology used, 802.11p or C-V2X, vehicles should switch to onboard sensor-based control in conditions when wireless connectivity is not available. This means an increase of IVDs in most cases. Using both available systems - onboard and wireless-based - that should back up each other for increased safety is a foreseeable practical approach. Developing algorithms for a fusion of those two systems is another direction for future work.

In addition to the aforementioned directions, the present study on ensuring safe cooperative driving of consecutive vehicles and the ethical V2X framework for addressing ethical dilemmas can be extended to more complex traffic scenarios, such as intersections or roundabouts. In such scenarios, a high level of planning combining control and communication should be done, where all road users and infrastructure can be viewed as multiple interacting intelligent agents. One promising tool for approaching complex traffic scenarios is machine learning, which can be used to effectively analyze vast amounts of data and adaptively optimize decision-making processes.

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**Part II**  
**Included Papers**



# Towards a Complete Safety Framework for Longitudinal Driving

Galina Sidorenko, Aleksei Fedorov, Johan Thunberg,  
Alexey Vinel

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"Towards a Complete Safety Framework for Longitudinal Driving", in *IEEE  
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## Emergency braking with ACC: how much does V2V communication help?

Galina Sidorenko, Daniel Plöger, Johan Thunberg,  
Alexey Vinel

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"Emergency braking with ACC: how much does V2V communication help?",  
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## ***Paper III***

# Vehicle-to-Vehicle Communication for Safe and Fuel-Efficient Platooning

Galina Sidorenko, Johan Thunberg, Katrin Sjöberg,  
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"Vehicle-to-Vehicle Communication for Safe and Fuel-Efficient Platooning",  
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# Safety of Automatic Emergency Braking in Platooning

Galina Sidorenko, Johan Thunberg, Katrin Sjöberg,  
Alekssei Fedorov, Alexey Vinel



# Ethical V2X: Cooperative Driving as the Only Ethical Path to Multi-Vehicle Safety

Galina Sidorenko, Johan Thunberg, Alexey Vinel

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"Ethical V2X: Cooperative Driving as the Only Ethical Path to Multi-Vehicle Safety",  
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## ***Paper VI***

# Cooperation for Ethical Autonomous Driving

Galina Sidorenko, Johan Thunberg, Alexey Vinel

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"Cooperation for Ethical Autonomous Driving",  
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