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Doctoral Thesis in Machine Design

Pre-crash Motion Planning for Autonomous Vehicles in Unavoidable Collision Scenarios

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Stockholm, Sweden 2022

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Abstract

Full deployment of Autonomous Vehicles (AVs) on public roads is challenging for organizations in the automotive domain in terms of developing safety standards and methods while taking legacy assumptions related to having a human driver and increased complexity and complexity handling into account. Specifically, the safety of AVs in the presence of other road users must be guaranteed as far as possible for different traffic scenarios. Furthermore, unsafe situations might emerge due to uncertainty in the environment of an AV. These situations could arise due to the unexpected behaviors of others (e.g., an aggressive driver), late obstacle detection, and internal failures. Avoiding a collision with other vehicles may thus not always be possible regardless of the complexity of the planned emergency maneuver.

This thesis aims to address the problem of motion planning and control for AVs in these unique situations of unavoidable collisions. Several factors that are important in the problem formulation of a pre-crash motion planning problem for severity minimization are identified and addressed. As a result, a framework is developed that incorporates these factors and combines motion planning and control, vehicle dynamics, and accident analysis to mitigate collision risk, in particular, by reducing injury severity for vehicle occupants and increasing safety by changing the configuration of unavoidable collisions.

This thesis tackles this problem by first proposing an algorithm that, in real-time, allows an AV to choose one action/trajectory, from a set of pre-computed trajectories, associated with the lowest injury severity for vehicle occupants. The method uses the trajectory library approach combined with numerical optimization and optimal control theories. The choice of this trajectory mainly relies upon a metric derived from accident data analysis that relates injury severity and impact location. By incorporating collision risk as a combination of collision severity and probability, the need for a configurable collision probability threshold that decides when a collision mitigation system should be activated is identified. This decision threshold balances the ability to reduce collision severity with the undesired increase in the likelihood of a collision taking place.

The studies included in this thesis show that different decision-making strategies involving decision thresholds for collision mitigation/reconfiguration systems can lead to statistically significant differences in the resulting collision severity. Furthermore, unobserved heterogeneity may arise through the introduction of these systems, e.g., due to slight variations in the parameters of the algorithms they employ. The problem of motion planning in unavoidable collisions is further extended by proposing a unified system that incorporates the risks of post-impact motions resulting from the original impact. The extended framework can be configured for different contexts by adjusting its cost function according to relevant post-impact risks.

The result of this thesis aims to contribute to the field of motion planning in unavoidable collisions and to provide guidance for further improvement of road safety. Further research is required to fully explore this field and address the challenges of motion planning and control in unavoidable collision scenarios.

Keywords:
Autonomous vehicles, motion planning, severity minimization, data-driven, safety, collision mitigation, vehicle dynamics, vehicle control, collision reconfiguration, post-impact, collision model

Sammanfattning

Att förverkliga kommersiell drift av autonoma vägfordon (AV) på allmänna vägar är en utmaning för organisationer i vägfordonsdomänen i fråga om att utveckla personsäkerhetsstandarder och metoder samtidigt som kvardröjande antaganden relaterade till existensen av en mänsklig förare, och ökad komplexitet och hantering av komplexitet, beaktas. Det som gör utmaningarna speciellt svåra att hantera är att AV i största möjliga mån måste kunna garantera att de inte påverkar personsäkerheten för andra trafikanter negativt i olika trafikscenarios. Dessutom, trots dessa garantier kan farliga situationer uppstå på grund av osäkerheten i miljön som AV rör sig i. Dessa situationer kan uppstå på grund av oförutsett beteende från andra (t.ex. en aggressiv förare), sen upptäckt av hinder, och interna fel. Att undvika en kollision med andra fordon är därför inte alltid möjligt oavsett komplexiteten i den planerade akuta undanmanövern.

Den här avhandlingen syftar till att adressera problembilden runt rörelseplanering och -kontroll av AV i dessa unika situationer där en kollision är omöjlig att undvika. Åtskilliga faktorer som är viktiga för formuleringen av en problembild för rörelseplanering, som utförs innan en oundviklig kollision och är ämnad att reducera omfattningen av skador, identifieras och adresseras. Detta har resulterat i utvecklandet av ett ramverk som integrerar dessa faktorer och kombinerar rörelse-planering och -kontroll, fordonsdynamik, och analys av olyckor för att mildra kollisionsrisk, specifikt genom att reducera skadeomfattningen för passagerare i fordon, och öka personsäkerheten genom att ändra konfigureringen av oundvikliga kollisioner.

Den här avhandlingen föreslår att problembilden hanteras genom en algoritm som, i realtid, låter en AV välja den handling/bana, från flera föruträknade manövrar, som kan associeras med den minsta skadeomfattningen för fordonspassagerare. Metoden använder sig av ett angreppssätt som kombinerar ett bibliotek av banor med numerisk optimering och optimal kontrollteori. Valet av bana baseras i huvudsak på ett mått härlett ur analys av data från olyckor som relaterar skadeomfattning till var på fordonet en kollision inträffar. Genom att inkludera kollisionsrisk som en kombination av en kollisions skadeomfattning och sannolikhet, identifieras behovet av en konfigurerbar tröskel för kollisionssannolikhet som kan avgöra när ett system för att mildra effekterna av kollisioner bör aktiveras. Denna tröskel balanserar möjligheten att reducera omfattningen av skador orsakade av kollisioner med en relaterad, oönskad ökning av sannolikheten att kollisioner inträffar.

Studierna som lagts samman i den här avhandlingen visar att olika strategier för beslutsfattande, när en tröskel för kollisionssannolikhet används i ett system för att mildra effekterna av kollisioner, kan leda till statistiskt signifikanta skillnader i omfattningen av de skador som orsakas av kollisioner. Oobserverad heterogenitet kan dessutom uppstå när dessa system introduceras, t.ex. på

grund av små variationer av parametrarna i algoritmerna de använder sig av. Problembilden runt rörelseplanering när en kollision inte kan undvikas utökas ytterligare genom att ett enhetligt system föreslås, vilket även kan hantera risker relaterade till de rörelser som kommer efter och beror på denna initiala kollision. Det utökade ramverket kan konfigureras för olika kontexter genom att dess kostnadsfunktion justeras utifrån de risker som är relevanta efter en initial kollision.

Resultaten som presenteras i den här avhandlingen syftar till att bidra till forskningsfältet runt rörelseplanering innan oundvikliga kollisioner och tillhandahålla vägledning för ytterligare förbättring av vägsäkerhet. Ytterligare forskning behövs för att helt utforska det här forskningsfältet och adressera utmaningarna för rörelse-planering och -kontroll i scenarier som involverar oundvikliga kollisioner.

Nyckelord:
Autonoma fordon, rörelseplanering, skademinimering, datadriven, personsäkerhet, säkerhet, mildring av effekterna av kollisioner, fordonsdynamik, fordonskontroll, omkonfigurering av kollisioner, efter kollisioner, kollisionsmodell

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I arrived in Stockholm on May 7th on a sunny day and I coincidentally ended up writing this acknowledgment on May 7th years later. These years have been full of experiences with many ups and downs. I am grateful for everything I have learned and everyone who played a role in that.

Masoumeh Parseh
Stockholm, May 7th, 2022

List of Appended Papers

This thesis is based on the following publications.

Paper A

M. Parseh, F. Asplund, and M. Törngren, "Industrial Safety-related Considerations to Introducing Full Autonomy in the Automotive Domain". *Ada User Journal*, vol. 38, no. 4, pp. 218-221, 2017.

Masoumeh Parseh performed the research and wrote the paper. Fredrik Asplund supervised the research, and contributed to analyzing the interview data and paper writing. Martin Törngren was involved in the discussion of the research and provided feedback on the paper drafts.

Paper B

M. Parseh, F. Asplund, M. Nybacka, L. Svensson and M. Törngren, "Pre-Crash Vehicle Control and Manoeuvre Planning: A Step Towards Minimizing Collision Severity for Highly Automated Vehicles," *2019 IEEE International Conference on Vehicular Electronics and Safety (ICVES)*, 2019, pp. 1-6.

Masoumeh Parseh performed the research and wrote the paper. Fredrik Asplund reviewed the paper and provided feedback. Mikael Nybacka provided guidance on vehicle dynamics modeling and implementation and provided feedback on the paper draft. Lars Svensson provided valuable inputs for the formulation of the trajectory library. Martin Törngren was involved in the overall discussion of the paper and provided feedback.

Paper C

M. Parseh, F. Asplund, L. Svensson, W. Sinz, E. Tomasch and M. Törngren, "A Data-Driven Method Towards Minimizing Collision Severity for Highly Automated Vehicles," *in IEEE Transactions on Intelligent Vehicles*, vol. 6, no. 4, pp. 723-735, Dec. 2021.

Masoumeh Parseh performed the research and wrote the paper under the supervision of Fredrik Asplund. Lars Svensson and Fredrik Asplund contributed to paper writing and helped with revisions. Wolfgang Sinz and Ernst Tomasch collected and analyzed the accident data. Martin Törngren was involved in the overall discussion, provided feedback on paper draft, and setup the collaboration with TU Graz.

Paper D

M. Parseh and F. Asplund, "Collision Mitigation in the Presence of Uncertainty," *2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2021, pp. 1655-1662.

Masoumeh Parseh performed the research and wrote the paper under the supervision of Fredrik Asplund. Fredrik Asplund contributed to paper writing and provided feedback.

Paper E

M. Parseh, and F. Asplund, "New Needs to Consider during Accident Analysis: Implications of Autonomous Vehicles with Collision Reconfiguration Systems", accepted for journal publication in *Accident Analysis & Prevention*, 2022.

Masoumeh Parseh and Fredrik Asplund developed the idea and wrote the paper together.

Paper F

M. Parseh, M. Nybacka, and F. Asplund, "Motion Planning for Autonomous Vehicles with the Inclusion of Post-impact Motions for Minimizing Collision Risk", under review in *Vehicle System Dynamics* for possible journal publication, 2022.

Masoumeh Parseh performed the research and wrote the paper. Mikael Nybacka contributed to vehicle dynamics modeling and the overall conceptualization of the paper. Fredrik Asplund was involved in the overall discussion of the paper. All co-authors contributed to the draft of the paper, reviewed the manuscript, edited/added text and provided feedback.

Contents

Nomenclature

Abbreviations

$ADAS$	Advanced Driver Assistance Systems
AIS	Abbreviated Injury Scale
AV	Autonomous Vehicle
CAV	Connected and Automated Vehicle
CDC	Collision Deformation Classification
CMS	Collision Mitigation System
CRS	Collision Reconfiguration System
CV	Conventional Vehicle
DOF	Degrees-of-Freedom
$DRAC$	Deceleration Rate to Avoid Crash
GPU	Graphics Processing Unit
$IGLAD$	Initiative for the Global harmonization of Accident Data
ISS	Injury Severity Score
$MAIS$	Maximum Abbreviated Injury Scale
MPC	Model Predictive Control
$MPrISM$	Model Predictive Instantaneous Safety Metric
$NASS$	National Automotive Sampling System
$NHTSA$	National Highway Traffic Safety Administration
NLP	Nonlinear Programming

OCP	Optimal Control Problem
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
$PDOF$	Principle Direction of Force
PRM	Probabilistic RoadMap
$QCQP$	Quadratically Constrained Quadratic Program
RQ	Research Question
RRT	Rapidly-exploring Random Tree
$SaFAD$	Safety First for Automated Driving
SDG	Sustainable Development Goal
SSM	Surrogate Safety Measure
$STRADA$	Swedish Traffic Accident Data Acquisition
TTC	Time-to-Collision
$VDCS$	Vehicle Dynamics and Control System

Chapter 1

Introduction

This thesis focuses on mitigating the consequences of collisions in critical traffic situations involving unavoidable collisions. This chapter provides a brief introduction to this topic and motivates the research of this work. Furthermore, scope and delimitation, research questions, research contributions, sustainability considerations, and outline of the thesis are presented in this chapter.

1.1 Background and Motivation

The National Highway Traffic Safety Administration (NHTSA) published a report in which errors of the human driver were identified as contributing to 94% of approximately 2,046,000 crashes [1].[1] However, it is emphasized in [1] that "in none of these crashes was the assignment intended to blame the driver for causing the crash." The causes of these errors were identified and categorized as: recognition, decision, performance, and non-performance errors. The remaining 6% was almost equally divided between vehicles, environment, and unknown critical reasons. Furthermore, all operational design domains (ODDs) are susceptible to human errors [4].[2] Traffic safety is already improved by the introduction of several Advanced Driver Assistance Systems (ADAS) such as anti-lock braking, blind spot detection, adaptive cruise control, and advanced emergency braking [6]. ADAS provide supporting information for drivers and

[1] It is emphasized that these crashes are not simply caused by reckless driving [2]. Causes such as "decision error" and "recognition error" also contribute to this number. Therefore, the actual crashes that can be eliminated by autonomous vehicles are much lower than 94%. Crashes primarily caused by human error such as "impaired driving" or "violating traffic rules" are estimated to be approximately around 50% [2], [3].

[2] According to SAE J3016 [5], ODD is defined as "Operating conditions under which a given driving automation system, or feature thereof, is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."

assist them in making critical actions [5]; they belong to a lower level of automation. For high levels of automation (high automation as level 4 and full automation as level 5), the vehicle can perform all driving tasks under certain/all driving conditions [5].

Waymo, as one of the leading developers of automated driving systems, performed a simulation study in which fatal accidents during the years 2008-2017 were reconstructed [4]. Human-driven vehicles were replaced by Waymo's fully automated vehicles. They showed that 92% of the simulated collisions, in which the human drivers were the initiator of the accidents, were avoided (82%) or mitigated (10%). Therefore, the introduction of Autonomous Vehicles (AVs) bears the promise to drastically reduce the frequency and severity of accidents caused by human errors [7]. AVs as the future of road transportation safety bear the promise to contribute to passenger comfort, congestion reduction, improved mobility, and environmental factors [8]. These reasons have led to significant industrial efforts to introduce such technology and the rapid development of AVs for the past two decades [9]. Several major companies such as Google, Tesla, and Uber have already contributed to the progress of driving autonomously on public roads [10]. However, according to [11], it is still unclear how AVs contribute to some of these reasons, for instance, reducing congestion without being connected and collaborating. Financial benefits were also identified as a contributing factor that drives the deployment of AVs [11].

The introduction of AVs simultaneously imposes several challenges for industrial stakeholders. Several of these challenges are identified and discussed in [12], [13]. When it comes to safety methodologies for AVs, Waymo argues that no single safety methodology is holistic enough to demonstrate that an AV is safe [14]. Therefore, a combination of several methodologies is used by them to ensure the safe performance of AVs on public roads. Furthermore, [14] also argues that even though the ISO26262 standard provides significant insights for hazard analysis strategies, it is not the best fit for level 4 of automated driving systems. Furthermore, Safety First for Automated Driving (SaFAD) initiative [15] provides a foundation for overall safety by proposing several principles for automated driving under the concept of positive risk balance.[3]

The task of an AV can be categorized into three layers: perception, planning, and control [9]. A general overview of an AV system, referred to as core competencies [10], is presented in Figure 1.1. The first layer is responsible for gathering information about the environment by utilizing several sensors such as radars, lidars, and cameras. Data gathered from sensors or their fusion is used to understand critical information about the environment such as the position

[3]Positive risk balance is defined in [15] as "the result of a risk benefit evaluation with a lower remaining risk of traffic participants due to automated vehicles. This includes the fact that automated vehicles cause less crashes on average compared to the average human driver."

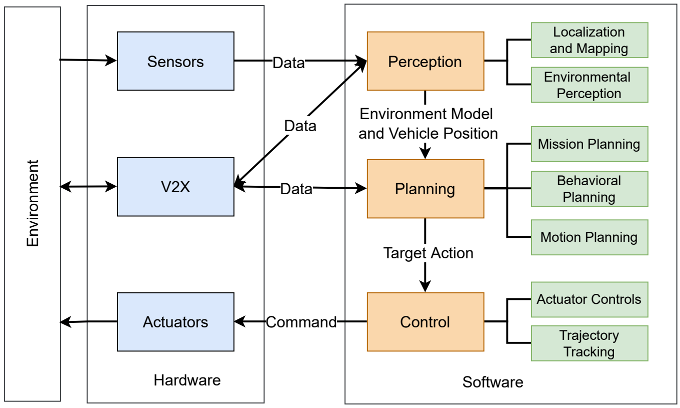

Figure 1.1: A general overview of an autonomous vehicle system. This graph is redrawn from [9], [10]. The hardware box includes what is usually referred to as the vehicle platform.

and velocity of obstacles and drivable areas [10]. Localization and mapping as part of the perception layer determine the global and local position of the vehicle and create a map of the environment [9], [10]. The planning layer can be categorized into mission, behavioral and motion planning [10]. Mission planning or route planning is described as finding a path that is associated with the minimum cost on a road network graph [16], [17]. The graph has nodes and edges. Nodes represent locations on the road, and edges connect these nodes. Each edge has a weight and the optimization problem is defined as going from a source node to a target node while minimizing the sum of these weights. After route planning, a driving behavior considering the behavior of other road users, traffic rules, and the conditions on the road is determined by the behavioral layer while making progress reaching the planned mission [10], [18]. The motion planning layer calculates a path or trajectory that represents the decided behavior, which is collision-free and should be feasible from the vehicle dynamics perspective. The control layer calculates the actuator commands such as steering and braking inputs for the vehicle to follow this trajectory [9].

All the above mentioned tasks of an AV are associated with several challenges, and proper research needs to be allocated to each one of them. Several of these challenges are identified in [9]. For instance, robustness, cost, object classification, and accuracy of sensors require further improvement. Furthermore, improvements in planning algorithms are needed to balance computational efficiency and accuracy of solutions. Decision-making must also be able to handle the uncertainty in the environment and unexpected behaviors of other road users. The need for a controller that is robust and highly fault-tolerant is also emphasized [9].

Safely maneuvering an AV is a difficult task due to the mentioned challenges combined with mixed traffic situations consisting of both AVs and human-driven vehicles, the uncertain and complex environment of roads, and other environmental factors such as weather and road conditions.

Research in motion planning in regards to collision mitigation has mainly focused on developing collision avoidance systems [19]–[23]. Others have taken the approach of contingency or fail-safe planning in which either the vehicle is brought to a stand-still position or an alternative trajectory is planned in parallel to the nominal trajectory [24]–[26]. Contingency planning is motivated by the requirement of NHTSA that AVs must have the ability to reach a minimal risk condition [27]. Furthermore, motion planning in critical situations [28], defined as "suddenly appearing situations caused by internal or external factors in which the probability of an imminent accident is substantially increased." has gained attention in recent years [29]. This planning requires performing prompt actions that reduce the possibility of a crash considering the physical limits of the vehicle [28].

Despite all advances that have been made in these fields and the complexity of maneuvers, it may be unrealistic to assume that all accidents can be avoided. The motivation behind this thesis is to reduce harm and injuries for humans and increase traffic safety in the complex environment of an AV. This goal is achieved by proposing a motion planning framework that tackles pre-crash scenarios, i.e., situations and maneuvers of the vehicle before an imminent crash [30], focusing on reconfiguring unavoidable collisions. Therefore, the goal of the appended papers and this thesis is to contribute to minimizing collision severity in such situations.

1.2 Thesis Objectives

The objective of this thesis is to reduce harm and injuries in road traffic and to contribute to road safety research involving AVs. This objective is formulated as a motion planning problem aiming at reducing collision severity in unavoidable crashes. Existing literature on several topics such as motion planning and control, vehicle dynamics, and accident analysis are studied and presented in Section 3.1 to 3.3 to achieve this goal. This is followed by identifying several research gaps within the current state-of-the-art (Section 3.4). Furthermore, characteristics of motion planning and control in unavoidable collisions are identified and used to develop a framework for severity minimization motion planning (Section 4.1). The appended papers of this thesis address different aspects of this framework and close the identified research gaps.

The remainder of this section discusses the scope and delimitations of this thesis, the research questions, the high-level contributions achieved through Paper A to F, and sustainability remarks.

1.2.1 Scope and Delimitations

The impact of vehicle automation on safety is investigated at three levels by [31]. The first level is the "vehicle" and focuses on the positive effects of AVs in reducing or eliminating driver-related errors. The second level is the "transportation" and investigates the effect of AVs on reducing traffic conflicts and crashes. The third level is the "society" which focuses on public health and changes in vehicle crashes. This thesis contributes to all three levels of automation regarding safety, directly or indirectly. On the vehicle level, this thesis has a positive impact on safety for AVs by performing research on this topic and proposing methods and algorithms aiming at increasing road safety. On the transportation level, the positive impact is achieved by addressing AVs' safety and performance in mixed-traffic scenarios, and on the society level by developing a framework that aims at reducing injury severity for occupants of vehicles.

In terms of research and development areas of AVs, this thesis has mainly focused on motion planning and control and specifically addresses planning in traffic scenarios when a collision is unavoidable. Route planning and behavioral planning are also parts of the planning layer. The route planning is associated with maneuvering within the road network and it is not required for motion planning in unavoidable collisions. Therefore, this planning is out of scope for this thesis. The behavioral aspect in terms of decision-making in the presence of other vehicles is considered in this thesis. However, behaviors of vulnerable road users such as pedestrians and cyclists are not part of this thesis. This is because including these factors requires comprehensive investigations and modeling of the kinematics of the human body for a vehicle to pedestrian/cyclist collision scenarios and different modeling of the injury severity. Furthermore, the details of this modeling are also affected by parameters such as age or gender. However, from a general point of view, it can be considered a similar problem. One example article that addresses unavoidable collisions in a vehicle-pedestrian accident is [32]. For vehicle control, as a part of motion planning and control, an optimal control approach is applied to generate states and actuator/control inputs of the optimal trajectory. Furthermore, this thesis addresses the effects of uncertainty on the decision-making strategies of AVs equipped with mitigation systems but does not focus on proposing new methods to handle/reduce uncertainty. Therefore, even though it is possible to include sensor errors and disturbances, it only affects the degree of uncertainty and *not* the generic results concerning decision-making strategies and thus motivates this delimitation.

In [33], sources of a hazardous event are categorized as internal, external, and a combination of the two. Furthermore, [28] defined three causes for critical situations: internal faults or performance limitations, aggressive or unsafe behaviors of other road users, and sudden changes in the environment of an AV. Sources of unavoidable collisions are closely related to the causes of critical situations. Therefore, the same categorization for causes of unavoidable collisions can be considered for this thesis. The appended papers of this thesis do not discuss a specific cause of an unavoidable collision. However, the assumption is that the sensing and vehicle dynamics capabilities of an AV equipped with the proposed systems/algorithms are not deteriorated by the cause of the unavoidable collision. These assumptions may thus position the cause categorization more on the side of unsafe behaviors of other road users.

1.2.2 Research Questions

Based on the aim and scope of this research, the following research questions (RQs) are defined.

RQ1 : Which are the most important factors that industrial stakeholders in the automotive industry must consider to allow for the introduction of fully automated vehicles?

RQ2 : Which are the most important factors to consider in the problem formulation of motion planning and control for an AV for minimizing collision severity in unavoidable collision scenarios?

RQ3 : If uncertainty is to be considered in the state estimation of surrounding vehicles, what is the effect of it on decision-making strategies and the activation time of collision mitigation/reconfiguration systems (CMSs/CRSs) of an AV?[4]

RQ4 : Considering RQ3, which are the most important factors that industrial stakeholders in the automotive industry must consider to allow for the introduction of collision mitigation/reconfiguration systems (CMSs/CRSs)?

RQ5 : If a motion planner should attempt to minimize severity across an entire accident scenario, which are the necessary components for post-impact motion planning and control?

[4]In this thesis and the appended papers, a collision mitigation system (CMS) and a collision reconfiguration system (CRS) are novel automation that aims to mitigate the severity of collisions. Reaching this state is often achieved by changing the configuration of the collision. In the context of this thesis, these two terms can be used interchangeably.

Appended Papers	RQs	Contributions
Paper A	RQ1	(i)
Paper B	RQ2	(ii), (v), (vi)
Paper C	RQ2	(ii), (v), (vi)
Paper D	RQ2, RQ3	(iii), (v), (vi)
Paper E	RQ2, RQ3, RQ4	(i), (iii), (v), (vi)
Paper F	RQ2, RQ5	(iv), (v), (vi)

Table 1.1: The relationship between the appended papers, the corresponding RQs and the high level contributions.

1.2.3 Research Contributions

The high-level contributions of this thesis can be summarized according to contributions (i) to (vi) as follows. The detailed contributions of each paper are addressed in Section 4.2. Furthermore, Table 1.1 presents the relationship between the appended papers, the research questions defined in Subsection 1.2.2 and the contributions presented in this subsection.

(i) The most important factors that industrial stakeholders must consider, in order to allow for: (1) the introduction of fully automated vehicles and (2) the introduction of CMS/CRS, are identified and discussed.

(ii) A specific and novel formulation of a motion planning problem for AVs in unavoidable collision situations is presented.

(iii) Decision-making strategies and activation time of an AV equipped with CMS/CRS under uncertainty are investigated.

(iv) The post-impact motions of vehicles involved in an unavoidable collision are incorporated in the pre-crash decision-making of an AV.

(v) The most important characteristics associated with motion planning and control in unavoidable collisions are identified.

(vi) A framework that combines the identified characteristics, regarding contribution (v), into a holistic method is developed.

1.2.4 Sustainability Considerations

This section briefly addresses the sustainability aspects of this research in connection to the UN Sustainable Development Goals (SDGs).

This thesis proposes a framework for pre-crash motion planning in unavoidable collisions and specifically focuses on reducing harm and injury severity for vehicle occupants in these scenarios. Therefore, this research directly or indirectly contributes to several of the UN SDGs.[5] These goals are as follows.

- Goal 3: "Ensure healthy lives and promote well-being for all at all ages."
- Goal 9: "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation."
- Goal 11: "Make cities and human settlements inclusive, safe, resilient and sustainable."

This thesis contributes to Goal 3 by performing research that focuses on reducing injury severity for vehicle occupants involved in road traffic accidents and contributes specifically to target 3.6, i.e.,"halving the number of global deaths and injuries from road traffic accidents by 2020" [34]. Achieving this goal consequently improves both road safety and the safety of AVs and reduces death and injuries caused by accidents. Furthermore, the safe deployment of AVs requires an efficient transportation system and the development of new infrastructure. This objective contributes to Goal 9 by supporting innovation, economic development, and human well-being. Goal 11 also targets improving road safety, attention to vulnerable situations, and access to a sustainable and safe transportation system. This thesis addresses Goal 11 at a higher level by performing research for AVs safety and directly through the objectives of this thesis and the appended papers. This thesis contributes specifically to target 11.2, i.e.,"to provide access to safe, affordable, accessible, and sustainable transport systems for all by 2030" [34].

1.3 Thesis Outline

The remainder of this thesis is as follows. Chapter 2 provides a summary of the research design that is applied in this thesis. Chapter 3 summarizes the state-of-the-art on existing research that is relevant for pre-crash motion planning in unavoidable collisions and presents the identified research gaps. Chapter 4 provides a summary of each paper and its contributions. This thesis concludes with a discussion, conclusions, and future research directions in Chapter 5.

[5] The numbers refer to the numbering of goals decided by UN SDGs.

Chapter 2

Research Design

This chapter presents the overall research design of this thesis and the appended papers. It starts by discussing research approaches from a philosophical point of view. This is followed by a discussion of the specific applied research methodology.

2.1 Research Approach

According to [35], research *approaches* are defined as "plans and procedures for research that span the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation." It consists of three main elements: philosophical worldviews, designs, and methods.

The Philosophical world view is defined as "a basic set of beliefs that guide actions" [36] and consists of four views: post-positivist, constructivist, transformative, and pragmatic. A researcher with the post-positivist view would start with a theory, collect data by empirical observations or measurements, and then reject or affirm a theory. It is mainly used for quantitative research and challenges the absolute truth of knowledge. A researcher with the constructivist view takes a qualitative approach to research. It heavily relies on the subjective view of the research participants and their experiences. It is often realized in collaboration/discussion/interaction with others. The transformative view focuses on policies and political changes to make life or work better for marginalized people and addresses important social issues. The pragmatism view is the one that is closest to the research performed in this thesis. In this view, the researcher is not limited or constrained to a specific philosophical view. By contrast, based on this view, research is realized within a context; the researcher has the freedom to choose different research methods and apply multiple techniques that best answer the research problem and the goal of the research. It also allows the researcher to collect different types of data and perform different data analysis methods. This view is usually associated with the mixed-method research design.

The research *designs*, also called "strategies of inquiry" [37], are categorized as quantitative, qualitative and mixed-methods. The quantitative design is associated with the post-positivist research view, where for instance investigating the relationship between variables is assumed to be the key to testing hypotheses and answering questions [35]. Experiments and non-experimental designs such as surveys are considered quantitative research. Some ways to conduct qualitative research are narrative research, grounded theory, and case studies. In a mixed-method design, researchers collect and analyze both quantitative and qualitative data. Ways to conduct mixed-method research are parallel, explanatory sequential, and exploratory sequential. In a parallel method, quantitative and qualitative data are usually gathered simultaneously. Then, findings from the gathered data are analyzed to interpret the final results. With the explanatory sequential method, quantitative research is conducted and analyzed by the researcher. This step is followed by qualitative research. In the exploratory sequential method, qualitative research is conducted first and analyzed to understand the views of the participants. This step is then followed by performing quantitative research. Following the pragmatic view and depending on the specific research problem being studied, both quantitative and qualitative data are collected and analyzed in this thesis.

The research *methods* are specific methods that the researcher selects for collecting, analyzing, and interpreting data [35]. The choice of the method can depend on several factors: nature of the study (pre-determined or emerging), open-ended questions versus closed-ended, and data analysis method (numeric or non-numeric based). For instance, the nature of the study is pre-determined in a quantitative method, while new questions can arise during a qualitative method. Ways to collect data can involve visiting a research site to observe the behaviors of individuals, conducting interviews, and performing tests. The collected data can be numeric or in the form of text, recording, etc. A statistical method may be used to analyze numeric data, or patterns and themes might be identified during data analysis. The research methodology applied for this thesis is presented in more detail in Section 2.2. The design of the study, methods of data collection, and data analysis are presented in Subsections 2.2.1, 2.2.2, and 2.2.3, respectively.

2.2 Research Methodology

This section aims to clarify the research methodology applied in this thesis and the appended papers. Given the exploratory nature of the research questions presented in Subsection 1.2.2, and the acceptance of the case study research method in the motion planning and control field, this research method is applied.

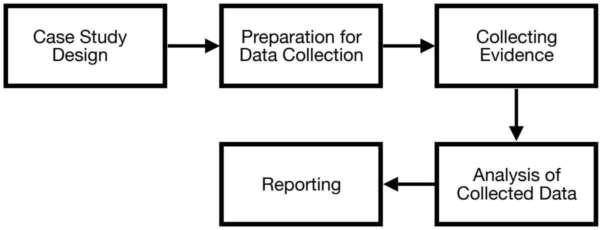

Figure 2.1: Phases of case study design.

This section starts by providing a definition of the case study research method and types of case studies. Afterward, the details of the case and methods for data collection and analysis are described.

The case study research method in this thesis follows the guidelines provided by [38]. A case study based on [38] is defined as "an empirical inquiry that draws on multiple sources of evidence to investigate one or multiple number(s) of instances of a contemporary software engineering phenomenon within its real-life context, especially when the boundary between phenomenon and context cannot be clearly specified." The nature of the case study can be exploratory [38]. When the nature of the research is exploratory, it focuses on identifying new insights and ideas, which are generated during the research phase.

Depending on the viewpoint of research, three types of case studies are defined by [39]: positivist, critical and interpretive. The positivist type of case study is associated with exploratory types of research purposes. A case study is considered positivist if evidence of a formal proposition exists; variables are measurable; hypotheses are tested, and conclusions can be drawn from a representative sample about a phenomenon [39]. In this thesis, an exploratory type of research along with a positivist type of case study is considered.

The phases of the case study method applied in this thesis are presented in Figure 2.1 based on [38]. Each phase is discussed separately in the following subsections. Validity is considered during all steps of the study and further discussed in Subsection 5.1.4.

2.2.1 Case Study Design

This subsection addresses several elements of a case study design. It should be noted that this design addresses the entire applied research from Paper A to F and follows the template provided by [38]. First, the rationale and the aim of the research are presented. Then, the studied case, the theory behind the research, and the research questions are introduced.

Rationale and Objective

Given the academic nature of the research performed in the papers of this thesis, the rationale of the study is to make a novel contribution to the existing knowledge by identifying and closing research gaps. These gaps are identified in the context of motion planning in unavoidable collisions and are presented in Section 3.4 and summarized in Subsection 3.4.5. The aim of this thesis is provided in Section 1.1 and then further refined by the research questions RQ1 to RQ5 in Subsection 1.2.2.

Case and Unit of Analysis

A case can be defined as anything that is a contemporary phenomenon in its real-life context [38]. The case in this thesis is defined as the *road traffic system*. The boundary of the case is not limited to the road structure and considers major actors involved in the development of AVs such as OEMs,[1] legislators, and traffic management.

First, to gain insights into the case and to achieve a broader perspective of the research problem, interviews were performed in Paper A. Then, two units of analysis as two road scenarios were defined for Paper B to F: intersection scenarios and a straight-road scenario with multiple lanes. This design is considered an embedded single case study, where both units of analysis are part of the same context. The former unit of analysis is applied in Paper B to E and the latter in Paper F.

The main motivation behind choosing an intersection scenario is its importance in accident research. [40] showed that accidents at intersections constitute 50% of all collisions. Furthermore, in a pre-crash scenario topology issued by NHTSA, *turning at non-signalized junctions* is considered the second most frequent accident among two vehicles when one is a light vehicle [41]. In addition, *Crossing paths* crashes, which often occur at intersections, are identified by [2] as one of the most challenging scenarios. Furthermore, as mentioned in Section 1.1, the simulation study performed by Waymo [4] showed the ability of automation to avoid collisions in approximately 82% of fatal real-world crash scenarios. The collisions that remained unavoidable were intersection, rear-end, and head-on collision types. For intersection scenarios, the automation was able to mitigate collision severity even though not enough time was available for complete collision avoidance. Therefore, there exists a possibility for mitigating collisions in these scenarios. In addition, the intersection scenario is commonly used in motion planning and control of AVs, e.g., [42], [43], to test methods and algorithms. Based on the above reasons, intersection scenarios are chosen as the main unit of analysis to perform the simulation studies (Paper B

[1] OEM stands for Original Equipment Manufacturer.

to E). The selection of this unit is further motivated by the availability of real accident data for these road scenarios.

The latter unit of analysis is better suited for Paper F due to being simple enough to evaluate the proposed method. In addition, it is widely used for the evaluation of algorithms in post-impact control applications [44], [45]. The intention was to extend Paper F to scenarios that also incorporate turning maneuvers for surrounding vehicles, for instance, intersections. However, due to modeling issues and complexity that emerged during the study, this extension is postponed for future research. This choice is aligned with the guidelines provided by [38], in which it is argued that cases can be removed or added due to practical constraints and the aim of the research. These new insights concerning the choice of this unit were achieved as the study progressed.

Theory and Research Questions

To better understand the context of the studied case and perform well-informed research, [38] suggests establishing an understanding of related work. During different stages of this thesis, several literature studies are performed. A state-of-the-art review (Section 3.1 to 3.3) and identification of knowledge gaps (Section 3.4) related to the field of motion planning in unavoidable collisions are presented in Chapter 3.

Research questions for this thesis are presented in Subsection 1.2.2. The research questions evolved as the study progressed and were refined in a way that by answering these questions, the objectives of the research and the case are met. The research questions are answered in Section 5.2.

2.2.2 Preparation for Data Collection and Collecting Evidence

In this thesis and through the appended papers, data is collected from three types of resources: interviews, simulations, and real accident data. In this subsection, the process of data collection for each type of data is discussed.

Interviews

The nature of the research in Paper A is more on the exploratory side and aims at understanding the challenges that exist for the studied case. The data for this paper is gathered by interviewing experts in the field. The experts were mainly from the automotive industry with the inclusion of a few ones from academia. The interviews were performed in two phases. The details of the first phase can be found in [46]. I designed the second phase of the interviews based on [47] and performed the interviews. The seven stages of interview research, as defined by [47], were followed in this study. These stages are: thematizing, designing, interviewing, transcribing, analyzing, verifying, and reporting. A brief description of these stages is as follows.

In the first stage, the purpose of the interview study was defined, and the research questions were formulated. Research question RQ1 was developed at this stage. In addition, several sub-questions were also defined based on this research question. In the second stage, investigations were performed to identify interview subjects, and the interview questions were formulated based on the research questions defined in the first stage. While designing the interview, all other stages were considered. Before conducting the interview, an interview guide was created. This guide includes the research questions, interview questions, and a visualization of how interview questions are related to the research questions. Besides the pre-determined questions, secondary questions were also asked during the interviews. These questions emerged as a result of the interviewees' responses. The interviews were performed face-to-face and recorded with the permission of the interviewees. Therefore, gathered data was in the form of audio recordings. The recordings were transcribed into written texts. Analyzing, verifying, and reporting the interview data is discussed in Subsection 2.2.3.

Accident Data

Another source of data collection in this thesis is real accident data, which is gathered from the Initiative for the Global harmonization of Accident Data (IGLAD) [48]. This database contains in-depth accident data from twelve different countries. At the time of data collection for this thesis, the majority of data in IGLAD was collected within Europe. In IGLAD, every single case consists of information about the accident (e.g., collision type, road type, and road condition), participant (e.g., vehicle mass, collision speed, Delta-V, and collision with CDC),[2] occupant (e.g., age, gender, and injury severity) and safety system (e.g., type, use, and activation). Data collection was initially performed for Paper C and further used in Paper D and E. Based on the objectives of the research, several filtering criteria are applied for the data collection, which is described in Paper C. It should be noted that after the accident data is analyzed, the result is used as inputs for algorithms in the simulation environment.

Simulation

The simulation environment is another source of data collection for Paper B to F. This simulation environment along with algorithms, road scenarios, and vehicle models were developed in MATLAB. The description of the simulation environment for individual papers can be found in the appended papers. The

[2] CDC stands for Collision Deformation Classification.

general setup includes an ego (own) vehicle, which is a highly automated vehicle equipped with the proposed algorithm/system. Depending on the context of the paper, one or multiple other vehicles exist in the surroundings of the ego vehicle. One assumption is that the surrounding vehicles are not equipped with the proposed algorithm/system. An unavoidable collision is the result of trajectories of other vehicles intersecting with those of the ego vehicle. To be able to define an unsafe situation such as an unavoidable collision for evaluating the proposed algorithm/system, simulation is chosen to avoid causing harm. The data is collected by running the simulation and is stored in the form of matrices, tables, and figures. Examples of collected data are injury severity, collision probability, collision risk, trajectories and states of vehicles, and actuation inputs. Some data was qualitative, e.g., heat maps, type of collision, or quantitative, for instance, collision severity values.

2.2.3 Analysis of Collected Data and Reporting

For the appended papers of this thesis, both qualitative and quantitative data were collected and analyzed. This subsection describes the process of data analysis for both types of data.

Interviews

The data gathered for Paper A is qualitative. As mentioned in Subsection 2.2.2, interview data was in the form of audio recordings and was transcribed into text. The data analysis for this paper focuses on *meaning*. Therefore, the transcribed text was coded to understand the meaning of the responses, and when combined with my understanding of the research topic provided new perspectives.

To analyze the transcribed text, the conventional content analysis method, described in [49], was applied. This method consists of coding, placing the text in meaningful categories, comparing them to identify relationships, and drawing conclusions from the text. Coding is the process of reading the transcribed text line by line, and attaching descriptive keywords by the side of the text to identify statements within the text at a later stage [47], [49]. Codes can be general or more specific, and they should be meaningful enough so that the researcher can understand the underlying meaning of the coded text. In Paper A, the naming of the codes was derived based on the transcribed text. After coding the text, it was possible to identify themes, patterns, and relationships. Generalizations were made by counting the number of times each code or category appeared in the text. A codebook was created containing code names, their interpretations, and the frequency of each code. A summary of inferences was written based on analyzing the codebook.

Accident data

After analyzing the accident data, a metric that relates the injury severity of vehicle occupants to the impact location of the vehicle was created. This metric was then used as input for the developed algorithm in simulation. This process and how this metric is derived are described in Paper C. The results of this analysis are further used in Paper D and E. Data analysis was also performed that relates three factors: injury severity of vehicle occupants, impact location, and the principal direction of force (PDOF). However, such a detailed relationship was limited by the lack of data. Therefore, this result is not included in this thesis or the appended papers.

Simulation

The gathered data for Paper B to F is both qualitative and quantitative and is analyzed either qualitatively or quantitatively.

In Paper B and C, data is the output of simulation that resulted from implementing an algorithm/method described in that paper. The goal is to demonstrate that the proposed algorithm/method performs as intended. For instance, the intention is to show that the system can mitigate the severity of a collision. Paper D uses quantitative data such as injury severity, performs a qualitative analysis of this data, and visualizes it in the form of heat maps, which are constructed based on matrices containing collision severity values. The heat maps, as visualization tools, are generated for different decision-making strategies and are analyzed qualitatively. The data in Paper F, presented in the form of tables and figures, was analyzed qualitatively. Several accident scenarios with varying modeling and parameter choices were compared to identify situations with the lowest severity of secondary impacts.

The quantitative data for Paper E is the injury severity of vehicle occupants resulting from collisions. Statistical methods were used to compare the different decision-making strategies and to analyze if these strategies are statistically significantly different.

First, the Shapiro-Wilk's test, to check if the data is *normally* distributed, was performed. With the condition that it is normally distributed, a one-way ANOVA is used to determine whether the decision-making strategies are statistically significantly different. However, if the data is not normally distributed, a Mann-Whitney U test or a Kruskal-Wallis H test is applied [50]. Results of data analysis with the Shapiro-Wilk's test showed that the data is not normally distributed. Therefore, a Mann-Whitney U test or a Kruskal-Wallis H test was applied. Kruskal-Wallis H test is an extension of the Mann-Whitney U test and is applied when more than two independent groups need to be compared. Thus, only the Mann-Whitney U test is explained here. To use this test, three more assumptions must be valid: The dependent variable needs to be ordinal or continuous; the independent variable needs to define two categorical groups; the observations in each group should be independent of each other. In addition, it must be determined if the distributions have similar or different shapes from each other. If the distributions for two groups have the same shape, the Mann-Whitney U test is applied to compare the medians of the groups regarding the dependent variable. However, if the distributions have different shapes, then the mean ranks are compared. The results of these tests are demonstrated in Paper E.

To present the results of this case study design, as described in this chapter, scientific papers are written and discussed with experts. Furthermore, the contributions of this thesis are presented from a higher-level perspective in Subsection 1.2.3 and in more detail for each appended paper in Subsection 4.2. This thesis and the appended papers *report* on the study of motion planning related to unavoidable collisions.

Chapter 3

State of the Art

This thesis takes an interdisciplinary approach toward addressing the research problem of motion planning in unavoidable collisions.[1] To address this research problem several bodies of knowledge are required to collaborate to reach the common goal of reducing the severity of such situations. Figure 3.1 presents an overview of these disciplines identified during this thesis, although not all are discussed in detail.[2] This chapter aims to provide enough background on the state-of-the-art literature to position this thesis in these fields.

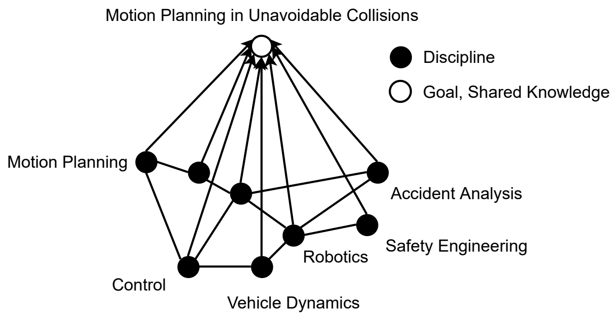

Figure 3.1: An overview of relevant disciplines for motion planning in unavoidable collisions. This graph is based on the interdisciplinary approach presented in [52].

[1]An interdisciplinary approach based on [51] is defined as "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice."

[2]Unlabeled nodes in Figure 3.1 refer to disciplines that are unidentified or not explicitly addressed in this thesis that can provide insights into the research of motion planning in unavoidable collisions.

This chapter is organized as follows. Section 3.1 elaborates on several techniques that are used in motion planning and control applications for mobile robots or AVs. Section 3.2 describes vehicle dynamics models that are common for planning and control application of AVs. Section 3.3 discusses several aspects of accident analysis that are used as guidance in this thesis. Finally, Section 3.4 outlines several research studies that are directly related to motion planning in unavoidable collisions and presents the existing research gaps.

3.1 Motion Planning and Control

This section presents a general definition of a motion planning problem in robotics in Subsection 3.1.1. This is followed by presenting and discussing several techniques that are widely used in motion planning and control in robotics/AVs applications in Subsection 3.1.2. This section ends with discussing a brief review of existing literature on contingency motion planning. The research problem of motion planning in unavoidable collisions can be considered a step beyond contingency planning. This discussion also allows the reader of this thesis to position this research within the topic of motion planning.

3.1.1 What is Motion Planning?

Considering robot $\mathcal{A}$ belonging to workspace $\mathcal{W}$, the basic motion planning (geometric path planning) problem can be defined as calculating a continuous path that is collision-free and takes robot $\mathcal{A}$ from an initial configuration (position and orientation) $\boldsymbol{q}_{init}$ to a goal configuration $\boldsymbol{q}_{goal}$ [53]. Both $\boldsymbol{q}_{init}$ and $\boldsymbol{q}_{goal}$ belong to free space $\mathcal{C}_{free}$, which is "the set of configurations that avoid collision" [53]. In this formulation, $\mathcal{C}_{free} = \mathcal{C} \setminus \mathcal{C}_{obs}$, where $\mathcal{C}$ is the configuration space ($\mathcal{C}$-space) and $\mathcal{C}_{obs}$ is the $\mathcal{C}$-space obstacle region. In path planning, the concepts of feasible and optimal planning are introduced [54]. The former focuses on generating a path that is feasible given the constraints of the problem, and the latter generates a feasible path that minimizes a cost function [18], [54].

Given that the motion of the robot is constrained by kinematics and dynamics limitations, motion planning under differential equations is needed. Therefore, motion planning and control under these conditions can be represented by the task of generating a path that connects the initial and final states under differential constraints [55]. The differential equation is formulated as $\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u})$, where $\boldsymbol{x} \in \mathcal{X}$ is the state vector, representing motion of the robot, and $\boldsymbol{u} \in \mathcal{U}$ is the control input [28]. In this formulation, $\mathcal{X}$ is the state space and $\mathcal{U}$ is the action space or the control commands of the robot. Calculating the future state and control inputs of the robot must satisfy both global and local constraints. Satisfying the global constraints means that the generated future states of the robot must be collision-free, and satisfying local constraints means that kinematics or dynamics of the robot and its limitations must be satisfied [18], [56].

Motion planning can be in the form of path planning or trajectory planning [57]. In the former, the solution is a path and does not describe how this path should be followed. In the latter, the solution is a trajectory that describes the evolution of the vehicle in time. Trajectory planning is more suitable for incorporating vehicle dynamics constraints and the environment of the vehicle. This thesis considers motion planning in terms of trajectory planning.

3.1.2 Motion Planning Techniques

A brief overview of different motion planning techniques is provided in this subsection. This categorization is based on [18], [28] and [56].

3.1.2.1 Trajectory Rollout

The trajectory rollout method can be categorized into three main groups [28]: state-space sampling, control space sampling, and trajectory library. These methods consist of three main steps and are different in the way the first step is performed [26]. The steps are first introduced, and then each method is discussed based on existing literature.

1. Trajectory propagation: A set of candidate trajectories that the vehicle can follow are generated from its current state.

2. Collision check: Information on obstacle location is gathered. Which trajectories collide with obstacles and which are collision-free are identified. Trajectories that are not collision-free are removed.

3. Trajectory selection: From the set of collision-free trajectories, the one with the lowest cost, given a cost function, is chosen. The cost function can be defined with respect to, for instance, progress to a goal location, distance from obstacles, preferred input, etc.

A hierarchical motion planner consisting of a global and a local planner is introduced in [58]. The former focuses on reaching the goal of motion planning and produces a large set of trajectories covering a longer time. It applies a simple vehicle model and a basic representation of the environment. The latter focuses on the safety of the vehicle and generates short-term trajectories. It uses a high degrees-of-freedom (DOF) vehicle model and a high resolution of the environment. For the local motion planner, the constraints can be expressed both in state space and control space. The state-space constraints are associated with the environment, and the control space is associated with the vehicle's abilities.

For the state space sampling method, the driveable area in front of the vehicle is discretized. Thus, the environmental constraints are satisfied. A set of boundary value problems is solved, where one boundary is the current state of the vehicle, and the other is a set of goal locations. Goal locations belong only to the allowed sections of the road. However, the generated trajectories can still be infeasible if one considers vehicle dynamics constraints [28], [58].

The control space sampling is based on discretization of the vehicle input space ($\mathcal{U}$), for which vehicle dynamics limitations are considered. For each discretized value of the control input, a set of trajectories is generated from the current state of the vehicle. Thus, the generated trajectories are feasible, however, environmental constraints cannot be guaranteed [28], [58].

These two methods are visually compared in [58] for a dense road environment. Trajectories generated by the state space sampling remain within the boundary of the road, while many of the ones generated by control sampling can be outside the boundary of the road. Furthermore, since only one trajectory is chosen from the set of trajectories, the design of the search space matters for the sake of computational efficiency. For example, by proper separation of the goal locations in state-space sampling, the overlap between trajectories is avoided, and computational efficiency is improved [58].

The method of trajectory library is an efficient way of applying the state space sampling method for trajectory generation. In this method, a more accurate vehicle dynamics model can be used by solving the boundary value problem offline and storing the resulting set of trajectories in a trajectory library. During the run-time operation of the vehicle, the desired trajectory is chosen from the set. In this way, high accuracy is reached and the computation time during run-time is reduced. This method has been applied in several fields, and its efficiency is proven. Examples of these applications are in robotics [59], [60], AVs [26], [61], and quadrotors and helicopters [62]–[64]. The use of the trajectory library approach concerning this thesis is further discussed in Subsection 5.1.1.

3.1.2.2 Numerical Optimization

Optimization methods have been widely used in motion planning and control applications for mobile robots and AVs. In this subsection, a definition and an example problem formulation are provided. Subsequently, several research studies, as examples, are discussed to better understand the characteristics of the problem formulation. The applicability of the optimization method in relation to this thesis is further discussed in Subsection 5.1.1.

Optimization methods are based on minimizing or maximizing a cost function while being subjected to vehicle dynamics or environmental constraints [56].

Thus, the motion planning problem can be formulated as an optimal control problem (OCP) with constraints on states and controls [28]. An example problem formulation is presented in Eq. (3.1), where J represents the cost function, $\boldsymbol{x}$ is the state and $\boldsymbol{u}$ is the control, which are constrained by vehicle dynamics limitations or environmental factors. The equations of motion of the vehicle are incorporated in f. Optimization problems can be solved by numerical optimization methods and several optimal control toolboxes [65]–[73]. By solving Eq. (3.1), the states and actuator inputs of the vehicle are generated.

$$\begin{aligned} \underset{u_1,\ldots,u_N,x_1,\ldots,x_{N+1}}{\text{minimize}} \quad & J \\ \text{such that,} \quad & x_{k+1} = f(x_k, u_k), \\ & x_k \in X, \quad u_k \in U, \\ & \forall k \in \{1, 2, ..., N\}, \\ & x_1 = x_{init}, \quad x_{N+1} = x_T. \end{aligned} \tag{3.1}$$

An OCP for obstacle avoidance is proposed for an AV in [74]. The optimization problem is multi-stage, and vehicle dynamics limitations, sensing, and control delays are incorporated in the problem formulation. The OCP is then transferred to a nonlinear programming problem (NLP) using direct methods and consequently solved with interior point methods. The optimization-based formulation has also been used in autonomous racing applications [61], [75]. In [61], Model Prediction Control (MPC)-based controllers are used to calculate the control inputs while maximizing progress on the race track under the constraints of actuators and the environment. Furthermore, the optimization problem is constructed as a tractable convex optimization (convex quadratic program). In [75], a rapid re-planning method for AV is proposed with the incorporation of friction limit and road geometry. The optimization problem is formulated as a convex quadratically constrained quadratic program (QCQP). The cost function is a second-order approximation of the change in the predicted time travel over a fixed planning horizon. Vehicle dynamics limits are encoded by linear equality constraints. The constraints on road edges and limits on acceleration and velocity are incorporated by box constraints. The authors showed that their method allowed the AV to respond quickly to rapid changes in the environment, for instance, sudden obstacles appearing, changes in the level of grip, and tracking errors. According to [75], this further increased the chance of avoiding obstacles for AVs in emergency scenarios.

3.1.2.3 Graph Search

In graph search methods, the configuration space of a robot/vehicle is discretized into a graph. Each graph consists of vertices and edges. Each edge has elements of origin, destination, and path that connects the origin and destination. The generated path or trajectory, resulting from connecting sequences of edges, always belongs to $\mathcal{X}_{free}$ and satisfies the differential constraints [18], [56]. The graph search algorithms that exist in literature are: Dijkstra[76]–[78], A* family [79]–[83] and state lattice [84]–[87]. Here, these algorithms are briefly described based on existing literature.

The original Dijkstra algorithm finds the shortest path between two given nodes (P and Q) [76] in a graph with R being a node on this shortest path. If the shortest path is known, the path from P to R is also known. Adaptations of this algorithm find the shortest path from a single source to a single destination.

The A* algorithm is an extension of the Dijkstra algorithm [88] and due to its use of heuristics has better performance. This means that this algorithm chooses a path that minimizes $f(n) = g(n) + h(n)$ function, where n is the next node, $g(n)$ is the cost from the source to n, and $h(n)$ is the lowest cost from n to the goal. However, a disadvantage of both Dijkstra and A* is that the resulting path is not continuous [56]. Hybrid A* is an extension of A*, where the state transition is continuous and not discrete [89], and the generated path is guaranteed to be feasible based on vehicle kinematics [90].

State lattice is a "directed cyclic graph" that satisfies the differential constraints by design [84]. It is a search space that is constructed by discretizing the configuration space into nodes [91]. Nodes represent discrete states and are connected by edges or feasible paths (motion primitives). It is assumed that this lattice contains all feasible paths considering a certain resolution. Any systematic graph search method such as A* can be used to search the state lattice [84], [92]. For a robot/vehicle that travels from one node to another, a sequence of feasible paths is available [92]. Furthermore, a cost map can be generated for the state lattice, which for motion planning applications can be the least costly and obstacle-free path. A path sampling method is also needed that returns the cost of traveling across the path based on the cost of traversed cells [91].

For a lattice-based planner, the continuous-time optimal control motion planning problem is transferred into a discrete graph search problem [87]. The motion primitives, which are dynamically feasible trajectories, are calculated offline by solving a boundary value problem [84], [93]. This allows the planner to focus on environmental or obstacle-related constraints during online operation. Thus, a high-quality lattice sampling of the state space can be performed, and online computation is reduced [93].

One method to solve the boundary value problem for lattice-based planners is to use optimal control to generate the motion primitives [87], [94], [95]. For instance, a two-level optimization is proposed in [95], where a lattice-based planner is combined with an OCP. The solution of the lattice-based planner is given as a warm-start for the OCP. Given that the system dynamics and objectives were the same for both steps, the solution of the lattice-based step was very suitable for the OCP. Consequently, the computation time was reduced; better convergence of the OCP solver was achieved, and the solution of the path planning problem was improved.

The conceptualization of lattice-based planners is similar to the trajectory library method, described in Subsection 3.1.2.1. According to [28], the generated motion primitives or trajectories are valid, assuming that the robot/AV dynamics are constant between positions. In general, graph search methods are more suitable for long time planning [28]. Given the tight time constraints of unavoidable collisions, these methods are not well-suited for motion planning applications related to these scenarios.

3.1.2.4 Random Sampling

Two of the major random sampling algorithms are Probabilistic RoadMaps (PRMs) and Rapidly-exploring Random Trees (RRTs) [96]. Both algorithms are based on randomly sampling the configuration space of the robot to take the robot from an initial configuration (q_{init}) to a goal configuration (q_{goal}). However, they differ in the way they connect q_{init} to q_{goal} [97]. The details of each method and the pseudo code for each algorithm can be found in [98]. These methods are not well-suited for applications such as unavoidable collisions, where a more accurate dynamic vehicle model is needed.

The PRM consists of two stages: a construction phase and a query phase. In the first phase, an undirected graph is built based on randomly sampling the configuration space of the robot iteratively and checking for collisions. The valid configurations in the graph are called nodes and are connected by edges, which represent the set of collision-free trajectories and are generated by a local planner [99]. In the query phase, paths are generated between an arbitrary initial and goal point. This algorithm has probabilistic completeness, which means that if enough samples are collected probability of finding a solution converges to one [96], [97].

On the other hand, in the RRT method, the construction of the tree and searching for the path are performed in the same stage. First, a random configuration (q_{rand}) is sampled. Second, a search is performed in the tree to find the nearest node (q_{near}) to q_{rand}. Third, a new configuration (q_{new}) is created that goes from q_{near} towards the direction of q_{rand} with a distance of d by interpolation or by a local planner. q_{new} will be added to the tree if it is a collision-free configuration and if the path between q_{new} and q_{rand} is collision-free. The process is iterative and ends with either reaching q_{goal} or the maximum number of iterations [100]. This algorithm uses steering functions [100], [101] to connect configurations by assuming a Dubins vehicle model. Several extensions of this algorithm such as RRT* [102], P-RRT* [103], and

PQ-RRT* are [104] developed in the literature that further improves the RRT algorithm.

3.1.2.5 Interpolating Curve Planners

In this method, a set of pre-defined waypoints or a coarse planned path is available. A new set of data is then interpolated within the given points to generate a continuous and smoother path [56]. Several different techniques exist based on this idea, which are categorized as *Lines and Circles* [105], *Clothoids* [106], [107], *Polynomials* [108], *Bezier curves* [57], [109], [110], and *Splines* [106], [111]. The advantages and disadvantages of using each curve are discussed in [56]. To generate the speed profile along the path, speed, acceleration, jerk, and actuator constraints are considered [9]. Some example applications of these methods are as follows.

In [106], cubic splines, trigonometric splines, and Clothoids are used for trajectory planning. In terms of tracking and passenger comfort, all methods showed good results. However, the Clothoid method was complex and less flexible. According to [57], Bezier curves show better computational efficiency and are more suitable for online applications. For an AV modeled as a car-like robot, [111] applied a parametric spline method, where constraints were incorporated in path segments, for trajectory generation in an urban environment. Results showed that lateral acceleration and yaw disturbances were reduced and passenger comfort was improved. A two-stage motion planner, i.e., a path planner and velocity planner, for AVs in cooperative driving was introduced in [109]. The path planner applied a quintic Bezier curve and dynamic programming to generate a continuous path, and the velocity planner used MPC for an optimal velocity profile.

As seen from the above examples, these methods can be used for mobile robots/AVs in several applications, such as cooperative driving, overtaking maneuvers, and driving in urban environments. However, they are associated with less detailed vehicle dynamics models and thus are not well-suited for motion planning in unavoidable collisions.

3.1.3 Contingency Motion Planning

Contingency or fail-safe motion planning is defined previously in Subsection 1.1. To further position severity minimization motion planning in unavoidable collisions within the field of motion planning, a summary of several papers that address contingency planning is discussed in this Subsection.

A fail-safe motion planner is developed in [24] to safely bring the host vehicle to a stand-still. For collision avoidance, an optimal trajectory is generated based on the most likely maneuver of surrounding vehicles. With the formulation of the cost function, higher values of jerk are avoided, and deviation from the reference trajectory is penalized. An emergency maneuver is planned based on considering all possible maneuvers of the target vehicle. In the optimization problem for the emergency maneuver, the velocity is minimized; the set of all possible trajectories as constraints is incorporated; following the lane is no longer a priority.

A fail-safe trajectory planner for operating in an arbitrary traffic environment is proposed in [112]. To generate fail-safe trajectories in real-time, convex optimization is formulated, where longitudinal and lateral dynamics are decoupled and modeled linearly. For the longitudinal formulation, high values of acceleration and jerks are penalized, and constraints on acceleration and velocity ensure kinematic feasibility. For the lateral formulation, lateral deviation and orientation from the reference path are minimized while high curvature rates are penalized. The possibility of a collision-free braking maneuver to generate a fail-safe trajectory is checked. If that is not possible, the feasibility of a lateral motion is investigated. If the lateral motion is infeasible the previously calculated and valid fail-safe trajectory is executed. The authors argued that their method is computationally more efficient than known sampling-based methods.

The strategy proposed in [113] to compute contingency maneuvers has two steps: an offline phase where a set of motion primitives is generated, and an online search algorithm for collision checks. The motion primitives are generated by solving an initial value problem, where control inputs and initial conditions are sampled and equations of motion are solved. The authors showed that combining the search algorithm with the pre-computed motion primitives provided fast solutions.

Contingency planning in [114], [115] consists of obstacle prediction and path optimization. For obstacle prediction, discrete goal sets are defined based on road geometry, driver behaviors, or obstacle types. The motion of each obstacle is propagated in a probabilistic manner by using filtering methods. Path planning is formulated as an optimization problem, where paths are represented as cubic splines to allow for fast computation in real-time. For each goal set, a separate contingency path is planned. Given that the vehicle cannot follow several contingency paths simultaneously, a shared initial segment is enforced as a constraint. This design provides a deterministic path for AV for the current time step without compromising the independence of the contingency maneuvers for the future [114], [115]. According to the authors, this method is more beneficial compared to planning a single path that avoids all obstacles or a weighted combination of independent contingency paths. The former is too conservative, and the safety of the combined path is not guaranteed in the latter [114], [115].

In the above mentioned papers, contingency trajectories are mostly derived based on a simplistic vehicle model and favor a reduction of the computation time. Therefore, the vehicle may not be able to track the planned trajectory, especially in highly dynamic scenarios. For instance, the exactness of the vehicle dynamics model in contingency scenarios, where the limits of the vehicles are challenged is emphasized in [116]. A nominal and an evasive maneuver are calculated in parallel by the use of an MPC. In case of an emergency event, the contingency MPC returns a safe trajectory for the vehicle to follow, and otherwise, the desired nominal path is followed. Linearization of the vehicle model and tire forces in the MPC problem formulation led to predicting higher values for tire forces than what is physically available. This design consequently led to deviations from the planned contingency maneuver. As can be seen from the result of [116], even by incorporating more complex vehicle models than the ones in [24] and [112]–[115], it was difficult to track the contingency trajectory.

3.2 Vehicle Dynamics

Modeling the vehicle dynamics is an important aspect of any motion planning and control algorithm to represent the motion of the vehicle and address its physical capabilities. Several vehicle models with different levels of complexity are addressed in the literature. This section provides a brief introduction to some of these models. Furthermore, the accuracy and applicability of these models related to motion planning in unavoidable collisions are also discussed.

3.2.1 Kinematic Bicycle Model

A kinematic model is a mathematical representation of the motion of the vehicle without considering the effect of forces on the vehicle's motion [117]. The differential equations are according to Eq. (3.2), where (X, Y) represent the global coordinates of the center of mass, v is velocity, ψ is yaw angle, β is side slip angle, and l_f and l_r are the distance between the center of mass and front and rear axles, respectively. The control inputs are steering angle (δ) and acceleration (a). Various representation of this model is applied in the literature. The model in Eq. (3.2) is based on [118].

$$\begin{aligned}
&\dot{X} = v\cos(\psi+\beta), \quad \dot{Y} = v\sin(\psi+\beta), \\
&\dot{\psi} = \tfrac{v}{l_r}\sin(\beta), \quad \beta = \text{arctan}\left(\tan(\delta)\tfrac{l_r}{l_f+l_r}\right), \\
&\dot{v} = a.
\end{aligned} \tag{3.2}$$

Kinematic models are widely used in literature and for motion planning applications of AVs, [26], [119]–[123]. These models are more suitable for lower speed planning such as urban environment or parking [18]. For instance, when compared with a dynamic one for an MPC controller, results showed that the kinematic model discretized at 200 ms performs as well as the dynamic model discretized at 100 ms [124]. Furthermore, under wind track and sinusoidal experimental test, the controller was able to track trajectories at lower speed levels, however for higher speed levels, the error increased significantly, and the need for modeling tire forces was identified. When the kinematic model was compared with a complex 9DOF vehicle model [118], the results showed that this model generates a feasible trajectory for motion planning purposes, given that the lateral acceleration is below 0.5μg, where g is the gravity acceleration and μ is road friction coefficient. Therefore, a more accurate vehicle model is necessary for a higher level of acceleration.

3.2.2 Dynamic Bicycle Model

In higher speed scenarios, the assumption that the velocity at each wheel is in the direction of the wheel is no longer valid [117]. The dynamic bicycle model is derived based on Newton's second law. An example model, also used in this thesis, is presented in Eq. (3.3). In this equation, (X, Y) represents the position of the center of mass, ψ is the yaw angle, v_x, v_y and $\dot{\psi}$ are the longitudinal velocity, lateral velocity, and yaw rate, respectively. The steering angle is δ, F_{xi} is the longitudinal tire force, F_{yi} is the lateral tire force, m is the mass of the vehicle, I_z is the moment of inertia about z-axis, and l_f and l_r are the distance between the center of mass and front and rear axles, respectively. The control inputs are considered as the rate of change of steering ($\dot{\delta}$) and the rate of change of braking on the front ($\dot{F}_{x_f}$) and rear ($\dot{F}_{x_r}$) axles. In some applications, tire forces are defined as control inputs to reduce complexity [29]. The calculated tire forces are then used to calculate actuator inputs such as steering and braking.

$$
\begin{aligned}
&\dot{X} = v_x cos(\psi) - v_y sin(\psi), \quad \dot{Y} = v_x sin(\psi) + v_y cos(\psi), \quad \dot{\psi} = r, \\
&m(\dot{v}_x - \dot{\psi} v_y) = F_{x_f} cos(\delta) + F_{x_r} - F_{y_f} sin(\delta), \\
&m(\dot{v}_y + \dot{\psi} v_x) = F_{x_f} sin(\delta) + F_{y_r} + F_{y_f} cos(\delta), \\
&I_z \ddot{\psi} = l_f F_{x_f} sin(\delta) + l_f F_{y_f} cos(\delta) - l_r F_{y_r}, \\
&\dot{\delta} = u_1, \quad \dot{F}_{x_f} = u_2, \quad \dot{F}_{x_r} = u_3.
\end{aligned}
\tag{3.3}
$$

Lateral tire forces can be modeled linearly or non-linearly through linear and nonlinear tire models. Assuming linearity for tire models is valid when the side slip angle is lower than 5 $\deg$ and the slip ratio is less than 0.1 [9]. For larger values of slip ratio and side slip angle a nonlinear tire model is needed. Without going into the details of tire modeling, a simplified version of the Pacejka magic formula [125] tire model is presented in Eq. (3.4). Other parameters in Eq. (3.4) include normal force (F_{zi}), slip angle (α_i), tire stiffness factor (C_i), and acceleration (a_x). In Eq. (3.3) and (3.4), f and r represent front and rear axles, respectively.

$$\begin{aligned} F_{y_f} &= -sin(tan^{-1}(C_f \alpha_f))\sqrt{(\mu F_{z_f})^2 - F_{x_f}^2}, \\ F_{y_r} &= -sin(tan^{-1}(C_r \alpha_r))\sqrt{(\mu F_{z_r})^2 - F_{x_r}^2}, \\ F_{z_f} &= m\frac{gl_r - h_{cog}a_x}{l_f + l_r}, \quad F_{z_r} = m\frac{gl_f + h_{cog}a_x}{l_f + l_r}. \end{aligned} \tag{3.4}$$

Adaptations of the dynamic bicycle model have been used in the literature depending on the application and the studied research problem [29], [126]–[131]. For instance, to generate a contingency trajectory using an MPC controller, the equations of motion and the tire forces were linearized in [116]. This led to inaccuracies where the predicted tire forces were above the physical limitations of the vehicle. Collision avoidance for AVs using an MPC controller is addressed in [127]. A simplified nonlinear bicycle model with linearized lateral tire forces is used to generate safe trajectories. It is further assumed that v_x is constant; slip ratio is zero; δ is small, and tire slip angles of the left and right sides are equal. The model is compared with a CarSim vehicle model for an exponentially increasing sinusoidal steering angle input. The two models showed similar behaviors for lateral acceleration below $0.5g$ and tire slip angles below $4\,\mathrm{deg}$. However, the side slip angle and the yaw rate of the two models diverged for values of slip angle more than $4\,\mathrm{deg}$ [127]. This is because large steering angle input caused large values of tire slip angle that were above $4\,\mathrm{deg}$.

Decoupling the longitudinal and lateral dynamics is also a way of dealing with model complexity. For instance, in [126] the tire models are linear, and the longitudinal dynamic is decoupled from the lateral and yaw dynamic, meaning that the term $\dot{\psi} v_y$ in Eq. (3.3) is ignored. However, in contrast to [116], the friction circle limit is applied as a constraint in MPC to ensure that the tire forces do not exceed the physical limits of the vehicle. The authors argue that this model is sufficient for their application of high speed and a small angle cornering (change lane). For collision avoidance applications in critical scenarios, utilizing the physical limitations of the vehicle is necessary. This is developed in [29] by traction adaptive trajectory planning, where available values of tire forces are calculated based on road friction and thus are fully utilized.

3.2.3 Higher Fidelity Vehicle Models

As mentioned previously, the level of complexity of vehicle models is dependent on the application. In literature, models with higher degrees of freedom than the bicycle model such as 4DOF, 5DOF, 9DOF, and 14DOF have been used [44], [128], [132], [133]. Here, a 4DOF model, also applied in this research (Paper F), is presented, and the relationship between model complexity and application is briefly discussed.

The 4DOF model is presented in Eqs. (3.5)-(3.8), where ϕ is the roll angle, $\dot{\phi}$ is roll rate, T_w is track width, and h_{rc} is the distance from sprung mass to roll axis. The longitudinal and lateral tire forces are: F_{xi} and F_{yi} with $i = \{fl, fr, rl, rr\}$. For instance, lf refers to front left tire, rr is rear right tire etc. Furthermore, m_s is vehicle sprung mass, I_x is roll moment of inertia about x-axis, I_{xz} is product of inertia about x and z axes, K_s is the rotational stiffness, and B_s is rotation damping for sprung mass.

$$m(\dot{v}_x - v_y\dot{\psi}) = F_{xrr} + F_{xrl} + F_{xfr} + F_{xfl}. \tag{3.5}$$

$$m(\dot{v}_y + v_x\dot{\psi}) = m_s h_{rc}\ddot{\phi} + (F_{yfr} + F_{yfl}) + (F_{yrr} + F_{yrl}). \tag{3.6}$$

$$\begin{aligned} I_z\ddot{\psi} + I_{xz}\ddot{\phi} = l_f(F_{yfr} + F_{yfl}) - l_r(F_{yrl} + F_{yrr}) + \frac{T_w}{2}(F_{xfr} - F_{xfl}) \\ + \frac{T_w}{2}(F_{xrr} - F_{xrl}). \end{aligned} \tag{3.7}$$

$$I_x\ddot{\phi} + I_{xz}\ddot{\psi} = m_s h_{rc}(\dot{v_y} + v_x r) + m_s g h_{rc}\phi - K_s\phi - B_s\dot{\phi}. \tag{3.8}$$

The required model complexity for collision-free trajectory generation in online MPC applications is investigated in [128] for a four-wheel truck that is driving with constant speed in an unstructured environment. Different variations of a 2DOF model were compared with a 14DOF model. Their investigation showed that the inclusion of tire nonlinearity and longitudinal load transfer in a 2DOF model is necessary for accurate trajectory prediction and also for MPC-based collision avoidance algorithms. Regarding the former, assuming tire linearity and constant axle load for a vehicle traveling at a higher speed fails to safely navigate the vehicle in the presence of obstacles. Concerning the latter, this is necessary to utilize the physical limitations of the vehicle. In both cases, for lower speed or less challenging environments, the 2DOF model performed well when compared to a 14DOF model. In [132], six different combinations of chassis and tire models are investigated to understand the required vehicle dynamics complexity and the associated computational demand for time-optimal control trajectory planning in critical situations focusing on active safety systems. The most complex chassis model, is a 5DOF model considering longitudinal, lateral, yaw, roll, and pitch. The other chassis models are simplifications of this model by assuming no pitch or roll behavior. The results showed that modeling choices can lead to very different control strategies. An example is provided for the 5DOF model in combination with two different tire models. Furthermore, their results showed that the chassis models with load transfer are more dependent on the choice of the tire model, which as a result, affects the optimal solutions. In addition, the authors showed that yaw rate and body-slip angle, which are important for vehicle safety considerations, showed similar results for various models in aggressive maneuvers.

3.3 Accident Analysis

Accident data has widely been used for different research purposes. For instance, for predicting injury severity of crashes [134], evaluating the effectiveness of new active safety systems [135] or investigating the benefits of AVs in improving traffic safety [136]. In this section, several papers concerning aspects of accident data analysis that are applied in this thesis are briefly discussed. For severity minimization, crash factors and their relation to injury severity are considered in the problem formulation of motion planning. Thus, several of these factors are briefly discussed in Subsection 3.3.1. Afterward, a short discussion on crash types, severity, and frequency for AVs is presented in Subsection 3.3.2, in which analysis of accident data for AVs is discussed based on existing literature. This discussion provides an understanding of how the introduction of novel automation can affect crash severity, frequency, or types.

3.3.1 Crash Factors

Injury severity is often measured based on the Maximum Abbreviated Injury Scale (MAIS). MAIS is the maximal of the Abbreviated Injury Scale (AIS). AIS is an internationally accepted injury severity scoring system that classifies injury by body region concerning its relative severity [137]. This system is based on a 6-point scale, where 1 represents minor injury and 6 is the maximum. For instance, MAIS3+ means serious injury and a score of 3 or higher on AIS. Injury Severity Score (ISS) is also used to represent injury severity.[3] It is argued in [139] that ISS is more reliable for calculating injury severity than considering the most severe one.

Many crash factors contributing to injury severity of vehicle occupants were identified in [134] by analyzing data from the National Automotive Sampling System (NASS). Examples of such factors are Delta-V, i.e., the total change in vehicle's velocity, crash force direction, impact location, vehicle type, single or multiple impacts, seat-belt, age, and gender [134], [139]. These factors are inputs for algorithms that predict the injury risk of occupants.

Considering the impact location, the front of the vehicle is associated with lower injury severity due to the use of a seat-belt, airbag, and the energy absorption characteristics of the *front* of the vehicle [140]. Conversely, in a front-to-side crash, occupants involved in *side* crash are more seriously injured. According to [140], a very small percentage (2%) of people were seriously injured in *rear-end* crashes. In [139] the highest injury rates were associated with right and left impacts with 6.4% and 8.5%, respectively. Based on police data in Japan, [141] identified that the probability of severe injuries as a function of

[3] ISS is defined as the sum of the squares of the highest AIS scores for the three most severely injured ISS body regions [138]. It is evaluated on a scale of 1 to 75.

Delta-V is higher for side impacts than frontal and rear impacts. Studies based on Swedish Traffic Accident Data Acquisition (STRADA) [142] showed that 12% of accidents with ISS > 8 are head-on collisions or side collisions outside an intersection while only 1.1% of these severe accidents are rear-end crashes. According to [143], for a belted and single collision, as delta-V increases, a near-side collision has a higher severity than a front or rear collision. A higher risk for the driver is observed if the point of impact belongs to the front passenger side and driver side than when it belongs to the rear passenger side and rear corners of the vehicle [144]. Furthermore, [145] showed that impact location strongly affects the injury severity in near-side crashes.

The crash force direction is modeled as a clock. The 8-10 and 2-4 o'clock impacts are associated with the highest causality, 11-1 o'clock impacts are the second-highest and 5-7 o'clock are the least severe ones [134]. Furthermore, impact direction largely depends on impact location [145].[4] Crash-worthiness, i.e., the vehicle's ability to protect its occupants, and crash aggressivity significantly vary by vehicle type [144], where the dominant factor was identified as vehicle mass.[5] Delta-V is also widely used in predicting crash severity. However, it is very sensitive to measurements of the Principle Direction of Force (PDOF). The mass of the vehicles and crush values also affect this uncertainty but with less significance [146]. Age and gender also affect the injury severity of occupants [139], however more difficult to predict in the context of motion planning in comparison to vehicle-related factors.

3.3.2 Safety of Autonomous Vehicles

Accident data analysis involving both AVs and conventional vehicles (CVs) has shown that the rear-end crash type is more frequent than other crash types [8], [147]–[150]. For instance, [8] identified that this crash type is statistically significantly more frequent in mixed traffic involving both AVs and CVs compared to when only CVs are considered. Similarly, CVs rear-ending AVs is identified as the most frequent type of collision [147]–[149], and the most frequent pre-crash scenario for AVs [150]. Furthermore, there is a higher likelihood that an AV is involved in a rear-end crash when the automated driving system is engaged compared to when it is disengaged or the vehicle is a CV [149]. Human drivers driving closely to AVs with an unsafe speed [8], and incompatibility of the reaction time of human drivers and AVs [150] were identified as reasons for this type of collision. In most cases of a rear-end crash, AVs were in autonomous mode and not at fault [148]. In contrast, AVs were involved in fewer broadside impacts

[4]The impact direction is represented by the principal direction of the resultant force (PDOF) and causes displacement and crush on the damaged vehicle [145].

[5]Crash aggressivity is defined as "hazardousness that the subject vehicle imposes on counterpart vehicle(s) involved in the same crash" [144].

in comparison to CVs [149]. Furthermore, broadside impacts and collisions with pedestrians were statistically significantly more frequent with CVs [8].

Regarding the crash severity, it was identified in [151] that collision patterns of turning, multiple-vehicle collisions, dark lightning conditions with street lights, sideswipe, and rear-end collisions are associated with a higher proportion of injury severity. Furthermore, [152] identified that crashes leading to injuries are lower for AVs in comparison to CVs, while nonfatal injury rates were higher for AVs.[6] For connected and automated vehicles (CAV), the main factors contributing to the severity of crashes are collision location, driving mode, rear-end collision, roadside parking and one-way road [136].

When it comes to collision frequency, mixed conclusions were identified in literature regarding collision rates between AVs and CVs [31]. Accidents for AVs are reported by manufacturers, while accidents for CVs are reported by police. Therefore, accidents of CVs can be under-reported [31]. [152] identified that collision rates are higher for self-driving vehicles in comparison to CVs, while [153] concluded that the two cases are not statistically significantly different. In [152], the authors adjusted the crash data for CVs to account for under-reporting. In [153], the authors considered police-reportable crashes. Others have taken a different approach to analyze the collision frequency of AVs. For instance, by computing accident frequencies, it was identified that miles traveled by CVs are higher than AVs before facing an accident [147]. The number of disengagement of AVs was compared with the number of fatalities and road injuries. Based on this comparison, [154] realized that driving automation technology is less reliable than a human driver. However, this unreliability is significantly decreasing.

Furthermore, [151] emphasizes that analyzing collisions of AVs and identifying the related risk factors is quite challenging and complex and requires more collision report narratives.

3.4 Remarks on Research Gaps

Motion planning in a dynamically challenging environment has mainly been focused on collision avoidance [18], [19], [21], [119], [155]–[158]. Contingency motion planning, discussed in Subsection 3.1.3, takes a step forward towards reaching a minimal risk condition by planning alternative maneuvers [26], [42], [113]–[116]. Motion planning in critical situations [28], defined in Section 1.1, aims at planning a maneuver that reduces the probability of an accident and can be considered as an extension of contingency planning. For instance, [28] mitigates accident risk and increases the vehicle's ability to avoid collisions in

[6] It should be noted that [152] was a preliminary study performed in 2015 based on limited accident data.

such situations by adapting to varying road friction in real-time. However, regardless of how complex the emergency maneuver or the contingency trajectory is, accidents still occur. Research in motion planning related to unavoidable collisions can be positioned within this field, where the focus is shifted from collision avoidance to severity minimization. This section discusses related research on motion planning in unavoidable collisions and identifies several gaps in this topic. The previous literature presented in Section 3.1, 3.2, and 3.3, builds the backbone for these discussions.

3.4.1 Pre-crash Motion Planning

Motion planning in unavoidable collisions is understudied, with only a few research papers available [43], [126], [159]–[161]. An MPC-based motion planning problem for crash mitigation in unavoidable collisions for real-time applications is proposed in [126]. A crash severity index is defined including relative speed, relative heading angle, and mass ratio, and incorporated into the cost function of the optimization. [159] developed a crash severity map based on lateral offset and impact angle by using finite element simulations to reach the least severe collision configuration. Then, this map is used online to calculate the crash severity. Deformation of nodes in the passenger compartment is used as a measurement of crash severity. Considering right turn maneuvers in an intersection scenario, [161] addressed severity mitigation based on the relative heading angle in the presence of static obstacles. Bezier curves in combination with a kinematic bicycle model are used for trajectory generation. [126] is extended by [160], where a method is developed for changing the mode of driving between collision avoidance and collision mitigation. The crash severity index is improved by incorporating the impact location of the vehicle in combination with Delta-V. [43] considered the risk of injuries, where an injury probability is assigned to an object in the environment, e.g., car, pedestrian, cyclist, that is calculated based on impact speed and factors related to ethics, economy, and politics. The concept of Probability of Collision with Injury Risk is defined in [43] as the combination of the probability of occupancy and probability of severity.

The studies described in the previous paragraph address the main problem of motion planning in unavoidable collisions, i.e., they propose a trajectory that minimizes collision severity. However, several drawbacks are identified in terms of vehicle model complexity and crash characteristics.

Firstly, an unavoidable collision requires the vehicle to operate at its physical limits. In addition, the real vehicle should be able to follow the desired trajectory. However, in [159] the trajectory that leads to the optimized crash configuration is calculated based on a chain model. In this model, constraints on maximum yaw rate and acceleration, applied in generating the optimal trajectory, are derived from simulation studies of a nonlinear single track model. As discussed in Section 3.2, incorporation of tire forces is essential for model accuracy in challenging situations such as unavoidable collisions. Similarly, trajectory generation in [161] is based on Bezier curves and kinematic models. The vehicle model in [43] is 1DOF which only allows for longitudinal maneuvering. In [126], even though tire forces are included in the modeling, the longitudinal and lateral dynamics are decoupled, which is not well-suited for complex scenarios of unavoidable collisions.

Secondly, considering the modeling of crash characteristics, only the severity of frontal crashes [43], [159], or a specific class of vehicles [159] are considered. In [126], the crash direction is simplified to the relative heading angle to allow for the quadratic formulation of the cost function, and in [161], crash severity is determined solely based on the relative heading angle between the vehicles. In a recent extension of [126], impact location in terms of front, rear, the near, and the far side is included [160]. However, the investigated case of an unavoidable collision was limited to an animal appearing in front of the vehicle.

3.4.2 Probabilistic Motion Planning

Although research has proposed novel methods to reduce uncertainty [162], [163], motion planning for AVs in an uncertain environment is a challenging task [164]. [165] categorizes risk assessment methods for AVs into two groups based on how risk is quantified: as the probability of colliding with other vehicles and as the degree of violation from nominal behavior. An example of the latter is measuring risk as the degree of violating a safety constraint, for instance, a regulated safety specification [166]. This thesis is more aligned with the first category focusing on collision mitigation applications. In the context of this thesis, both the probability and severity of a collision are considered for risk assessment.

Much research for motion planning under uncertainty has contributed to improving safety and mitigating collisions [167]–[171]. For collision mitigation, many papers have focused on longitudinal control. For instance, in [172], the collision probability is used to calculate a safe speed and an acceleration profile for maneuvering AVs in clustered environments. In [173], a velocity controller is proposed, where an acceleration with a lower collision probability has priority over one with a higher probability. Similarly, in [174] the optimal speed control is derived based on collision probability between vehicles. However, for emergency scenarios, a backup trajectory is generated in [171] by using stochastic MPC in overtaking scenarios with both longitudinal and lateral control.

Furthermore, probabilistic motion planning in unavoidable collisions has not gained much attention [43], [175]. A probabilistic algorithm for frontal collision detection is proposed in [175]. If an unavoidable frontal collision is determined, an aggressive emergency braking command is applied. The authors of [43] proposed a probabilistic cost map, as described in Subsection 3.4.1, that also considers injury severity. An object in the environment is assigned an injury probability according to impact speed and ethical/economic/political factors. However, no distinction between impact locations is made in both research studies, and only frontal collisions are addressed. Furthermore, in [175] only a longitudinal control action is applied, and in [43] no control action is provided.

In addition, previous research has not addressed the activation time of a probabilistic CMS/CRS in unavoidable collisions. When to activate such systems must be addressed considering uncertainty. An earlier activation is associated with more uncertain decisions, but more actions/trajectories are available for the ego vehicle to select. By contrast, a late activation is associated with less uncertainty, but less variation in actions/trajectories exists for the ego vehicle.

3.4.3 Collision Mitigation/Reconfiguration Systems

The decision-making strategy for a CMS/CRS consists of two choices: (a) which actions to take to reduce collision severity and (b) the time to activate the system. In addition, these choices are affected by uncertainty. The former choice has gained some attention in recent literature, as discussed in Subsection 3.4.1. However, the latter choice, considering uncertainty, is not addressed, as it is pointed out in Subsection 3.4.2. Furthermore, several different decision-making strategies can be implemented to address these choices. Consequently, differences in decision-making strategies can lead to different outcomes in terms of accident scenarios and interactions with human drivers. Different decision-making strategies for CMS/CRS and their effects on the severity of unavoidable collisions have not been discussed in the previous literature.

Mixed conclusions were observed in the literature when collision rates of AVs and CVs were compared (see Subsection 3.3.2). One study ([152]) adjusted the accident data to consider under-reporting of accidents for CVs, while another study ([153]) did not make such assumptions but used police-reportable crashes for AVs. The former concluded that collision rates are higher for AVs, while the latter did not find the results to be statistically significantly different. This contradiction is evidence of the presence of unobserved heterogeneity for research that is conducted based on accident data.[7] This unobserved heterogeneity is especially a problem for a novel technology such as CMS/CRS due to not enough data being available. Consequently, different decision-making strategies and their algorithmic differences can be considered new sources of unobserved heterogeneity.

[7]Unobserved heterogeneity in the context of this thesis is defined as the existence of factors that are very difficult or impossible to detect, which can affect collision frequency or severity [176].

Literature studies presented in Subsection 3.3.2, addressing collision severity, frequency, and crash types for AVs, were performed based on a small set of accident data. When not enough data exists to quantify the safety benefits of a novel technology or to evaluate its effect on safety, Surrogate Safety Measures (SSMs) are used [177]. SSMs are derived from frequent but less severe events, i.e., traffic conflicts, that are used to predict the occurrence of severe but infrequent events such as accidents [178]. SSMs are categorized as time-based, deceleration-based, and energy-based. Time-to-Collision (TTC), Deceleration Rate to Avoid Crash (DRAC), and Delta-V are examples of time-based, deceleration-based, and energy-based SMM, respectively. Model Predictive Instantaneous Safety Metric (MPrISM) is a new SSM that is proposed for AVs [179], which is considered a high dimensional TTC.

It was highlighted in [177] that literature aiming at validating SSMs only considered CVs and not AVs in their studies. In addition, SSMs are affected by automation, for instance, the decrease in TTC [180]. Therefore, there is a need for new SSMs and the ones considered for CVs may not be applicable for AVs. Following this logic, using the same SSM for vehicles that are equipped with a CMS/CRS and vehicles that do not have any collision avoidance system can be inaccurate. Furthermore, a CMS/CRS can increase collision frequency for the sake of decreasing collision severity. However, most SSMs that were used for CVs do not take severity into account. This is also true for novel SSM for AVs such as MPrISM. Therefore, a substantial gap in the literature is the lack of SSMs that take severity into account.

3.4.4 Consideration of Post-impact Motions in Pre-crash Motion Planning

Motion planning for reducing the severity of an unavoidable collision is discussed in Subsection 3.4.1. If a collision is determined unavoidable, the resulting impact can deviate the vehicles from the original path, and thus can expose the vehicle occupants to secondary impacts. Therefore, to reduce the collision severity, the evolution of states and trajectories of the vehicles after an impact should also be incorporated in the pre-crash decision-making of an AV. Pre-crash trajectory planning based on post-impact motions has not been previously addressed in literature for motion planning for AVs in unavoidable collisions.

Post-impact vehicle control, where the ego (own) vehicle is impacted, to reduce risk of secondary impacts is addressed in several papers [44], [45], [181]–[187]. These studies are focused on proposing a new controller that brings the ego vehicle to its current lane after an impact. For instance, an optimization problem that minimizes the lateral deviation and aligns the vehicle's heading angle with multipliers of 180 deg is proposed in [185]. This formulation was further improved by preemptive control actions using linear MPC, defined as steering control, that generates a yaw motion before or at the early stages of the crash [44]. Consequently, lateral deviations were reduced, and the vehicle was stabilized. For vehicle stabilization, side slip angle, yaw rate, and roll rate were decreased by using differential braking and active steering [183]. Furthermore, to mitigate extreme values of yaw rate and side slip angle, a feed-forward-feedback controller was proposed in [188].

It was shown in [189] that equipping the ego vehicle with several vehicle dynamics and control systems (VDCS) for collision mitigation can improve occupant protection for the ego vehicle by reducing deformation, pitch angle, acceleration, and maximum yaw angle. However, it did not have significant effects on the deformation of the target vehicle. The maximum yaw angle, yaw rate, and yaw acceleration increased for the target vehicle in several cases compared with free rolling. Occupant kinematics were further included in the modeling in [190]. Simulation studies showed that VDCS improved the crash situation for the occupants in terms of injuries for the vehicle that is equipped with it. However, the crash situation was worse for the target vehicle, not equipped with VDCS, due to a slight increase in pitch angle, acceleration, and deceleration compared to free rolling. Although, the authors argued that the increase in these values was small and insignificant. Given that equipping the ego vehicle with such systems did not have any positive effects on the target vehicle, it is necessary to consider the severity of the target vehicle in the context of severity minimization motion planning. Previous research has only focused on the ego vehicle.

In post-impact motion control applications [44], [45], [181]–[187], several assumptions were made in regard to modeling the collision including its parameters such as contact friction (μ) or angle of contact plane (see Paper F). For example, contact friction or impulse ratio is one of the parameters that is needed in collision modeling. During a collision, a force is generated by friction, with an associated friction coefficient, and by "interlocking of the deformed parts" [191]. Research in accident reconstruction showed that this coefficient is very difficult to determine [192]. The importance of estimating it accurately, especially in sliding impacts, has been addressed in [191]. In addition, research in Paper F shows that the post-impact states and trajectories of the vehicles are sensitive to the value of these parameters.

Furthermore, different values for contact friction are recommended in the literature. For instance, $\mu = 0.4$ is suggested for collisions between two vehicles in [193]. A limit of $\mu = 0.5 \pm 0.1$ is recommended to distinguish between sliding and non-sliding impacts [194]. They also recommended $\mu \ll 0.6$ for sliding impacts and $0.4 < \mu < 0.6$ for non-sliding ones. Others have recommended $\mu > 0.6$ for non-sliding impacts [195]. In addition, experiments show that this coefficient can vary depending on collision configuration, e.g., a side collision or head-on [196]. Therefore, it is difficult to decide on a limit for contact friction by which sliding and non-sliding impacts are distinguished. Furthermore, to the best of my knowledge, research in post-impact motion planning did not distinguish between sliding and non-sliding impact. This is most likely due to the mentioned difficulties in modeling an impact and the gap that exists between post-impact motion control and accident reconstruction research.

From the above discussion, the following conclusions are established. (1) The collision has to be modeled accurately in terms of the choice of the model and the values of collision parameters. (2) Post-impact motions of vehicles are sensitive to these choices. Therefore, it is essential to determine these choices accurately for motion planning and control applications. To the best of my knowledge, the implications of these choices and the sensitivity of post-impact motions to them in the context of motion planning in unavoidable collisions have not been evaluated in the previous literature.

3.4.5 Summary

The research included in this thesis has identified several research gaps in the context of motion planning in unavoidable collisions. This subsection presents a summary of the identified research gaps.

(a) A limited number of papers exist that address the problem of motion planning in an unavoidable collision. Furthermore, these studies have simplified either vehicle model complexity or the modeling of the crash characteristics. A detailed representation of impact location and its relationship to severity is not considered in previous literature.

(b) To the best of my knowledge, two papers that address uncertainty and collision probability in the context of motion planning in unavoidable collisions exist. However, no distinction between different impact locations is made, and only frontal collisions are addressed in these papers.

(c) Considering gap (b) and in the context of probabilistic motion planning in unavoidable collisions, either no control action is provided or only longitudinal control is included in the previous literature.

(d) Considering gap (b) and in the context of probabilistic motion planning in unavoidable collisions, the activation time of a probabilistic CMS/CRS is not addressed in the previous literature.

(e) Different decision-making strategies for a novel CMS/CRS and how they affect severity are neither addressed in previous research nor are identified as a source of unobserved heterogeneity.

(f) Research has recognized that SSMs that are developed for CVs may not be suitable for evaluating the safety of AVs. Furthermore, most existing SSMs do not take severity into account. Considering that a novel CMS/CRS can increase collision frequency while reducing collision severity, there is a lack of SSM that takes severity into account for novel automation.

(g) In the context of motion planning in unavoidable collisions for AVs, previous research has not considered post-impact motions of an impacted vehicle as a part of the decision-making of a pre-crash [severity minimization] motion planner.

(h) Previous literature proposed several controllers for stabilizing an impacted ego (own) vehicle. As a result, several assumptions were made that simplified the modeling of the collision. However, previous research did not investigate the implications of these assumptions and the sensitivity of post-impact motions to these simplifications.

(i) Previous papers have recognized that equipping an ego vehicle with VDCS does not have positive effects on a target vehicle (impacted vehicle). To the best of my knowledge, reducing severity for a target vehicle has not been considered in the previous research in the context of post-impact severity minimization.

The intention of this thesis with addressing the above research gaps is to contribute to research on reducing the severity of unavoidable collisions for AVs. Papers B and C address research gap (a), Paper D aims at addressing research gaps (b), (c), and (d), Paper E addresses research gaps (e) and (f) while also contributing to research gap (d), Paper F addresses research gaps (g), (h), and (i). Furthermore, Paper C contributes to or influences all of the above identified gaps. As mentioned in Subsection 2.2.1, Paper A is an exploratory study that contributes to a better understanding of the research problem of this thesis.

Chapter 4

Summary of Appended Papers

This chapter first presents the characteristics and the framework of the pre-crash motion planning related to unavoidable collisions. Subsequently, the summary and contributions of each appended paper are discussed.

4.1 Motion Planning in Unavoidable Collisions: A Framework

Motion planning in unavoidable collisions is a challenging problem. This thesis identifies several factors that are important in the problem formulation of severity minimization motion planning. This section addresses these identified factors in subsection 4.1.1, followed by an introduction to the framework in subsection 4.1.2 that units these factors.

4.1.1 Characteristics

1. **Accuracy of vehicle dynamics:** Given the tight time constraint and close proximity of vehicles in an unavoidable collision, the vehicle model of an AV that is equipped with a mitigation strategy must be accurate enough to allow for full utilization of the vehicle's capability in order for the vehicle to perform dynamic maneuvers and follow the planned maneuver.

2. **Metrics for the severity of collision:**[1] If a collision is determined as unavoidable, an action/trajectory is executed by the vehicle equipped with a mitigation system that leads to the lowest severity for vehicle occupants

[1] In this thesis, the focus has been on reducing the severity of injuries affecting the occupants of the impacted vehicle.

involved in the collision. Therefore, a metric is needed that prioritizes one action/trajectory over another based on severity levels.

3. **Risk of collision:**[2] Given that the states of other vehicles are uncertain, collision probability needs to be combined with collision severity to allow for measuring the risk of an unavoidable collision.

4. **Activation time:** A collision mitigation/reconfiguration system must balance between not acting too late and too early. Thus, a well-timed activation that addresses the trade-off between collision probability and severity is needed. Activation time is affected by uncertainty.

5. **Outcome of decision-making strategies:** AVs can be deployed with different decision-making strategies for collision mitigation, i.e., methods to perceive when to act and how to act. The effects of these different strategies, which can lead to different severity outcomes, must be investigated.

6. **Severity of a secondary collision:** If an unavoidable collision is determined, the collision severity should be minimized across the entire accident. Thus, an action is required that also considers how the states of vehicles propagate after an initial impact and how much this action exposes these vehicles to a secondary collision.

7. **Accuracy of collision models and parameters:** To accurately predict how the states of the vehicles will develop after an impact, the collision itself and its parameters should be modeled or set correctly.

8. **Execution time:** Given the time constraints of an unavoidable collision, the execution time must be sufficiently short in order for the vehicle to be able to react in a dynamically changing environment.

4.1.2 Framework

The identified characteristics 1 to 8 are united to propose a framework for severity minimization motion planning in unavoidable collisions. Characteristics 1 to 7 are addressed directly while characteristics 8 is considered indirectly.

The framework uses a dynamic bicycle model with a Pacejka tire model to generate a set of trajectories for an AV offline (see Eq. (3.3) and Eq. (3.4) in Subsection 3.2.2). These trajectories are derived by solving an optimal control problem where the control inputs are the rate of change of braking and the rate of change of steering angle (see Paper B for the problem formulation). By taking

[2] In this thesis, the concept of risk is considered a combination of collision severity and collision probability.

the trajectory generation offline, a sufficient representation of vehicle dynamics that is suitable for the characteristics of an unavoidable collision is achieved (characteristic 1). Therefore, the execution time during the run-time operation of the AV is allocated to trajectory selection (characteristic 8). Since these trajectories represent the reachable positions, they are also used for collision detection and identifying the unavoidable nature of the collision. To define a metric for trajectory prioritization, severity is considered the injury severity of vehicle occupants. Several factors that affect injury severity are identified by performing an initial literature study in Paper B, and further by analyzing real accident data in Paper C (characteristic 2). In Paper B, the injury severity that is associated with impact location in terms of *front*, *side* and *rear* impacts are considered as the criteria for trajectory prioritization. In Paper C, a metric is defined based on an analysis of real accident data, which maps a detailed impact location to the injury severity of vehicle occupants (see Paper C for details). A weighted combination of this metric and the relative pre-crash velocities between the vehicles is used as a cost function that decides which trajectory has the lowest cost, i.e., the lowest injury severity. In the design of the cost function, the severity is minimized for the occupants of the impacted vehicle. This trajectory will be executed, and the required control inputs are provided for the trajectory following.

Decision-making in terms of which trajectory to follow is extended to include collision probability in Paper D (characteristic 3). To do so a nondeterministic trajectory prediction is performed, where the evolution of uncertainty is based on state-of-the-art filtering methods. For each trajectory along the prediction horizon, collision probability and severity are calculated (see Paper D for detailed calculation). The activation time of a CMS/CRS is evaluated by varying a collision probability threshold and the number of available actions/trajectories to reach this threshold (characteristic 4). The CMS is activated if the maximum collision probability for the required number of trajectories of the ego vehicle is equal to or larger than the collision probability threshold and none of the trajectories have zero collision probability. An early activation means fewer trajectories have reached a lower collision probability, while a late activation means more trajectories have reached a higher collision probability threshold. Three decision-making strategies that relate collision probability to collision severity are also proposed: (1) severity at the threshold, (2) least uncertain severity, and (3) equal parts uncertainty and severity. These methods and variations in their algorithmic parameters, e.g., prediction horizon and their effects on collision mitigation are evaluated qualitatively in Paper D and E (characteristic 5). Paper E extends the evaluation to quantitative methods and performs statistical analysis to identify differences in the outcomes when these methods are applied (characteristic 5). The severity of secondary impacts is incorporated as a cost function based on the post-impact states of the vehicles in

Paper F. These states are lateral deviation, heading angle, yaw rate, and side slip angle (characteristic 6). Given that the post-impact states are affected by how the impact itself is modeled, accurate collision models and collision parameters such as contact friction and contact plane angle are required (characteristic 7).

The accident data used for Paper C is collected from [48], and the algorithms and simulation scenarios for Paper B to F are developed and analyzed in MATLAB 2018b. The optimal control formulation for trajectory library generation is solved with the CasADi optimization toolbox [70] in MATLAB. The data for statistical analysis is transferred from MATLAB, in the form of tables, to Excel and then analyzed by SPSS Statistics. The details of data collection and analysis are discussed in Subsections 2.2.2 and 2.2.3.

4.2 Summary and Contributions of Paper A to F

In this section, a summary of each paper and how each paper contributes to the objectives of this thesis is provided. For details regarding each paper, readers are referred to the appended papers of this thesis.

4.2.1 Paper A

Paper A addresses challenges related to introducing highly automated vehicles within the automotive domain. Structured interviews were performed with experts within both industry and academia. As a result, concerns regarding the following topics were identified: standards, safety analysis methods, legacy assumptions related to having a human driver, and increased complexity and complexity handling. Expert opinions regarding each topic and the associated challenges are addressed and analyzed in Paper A. The need for new standards is motivated by the introduction of autonomy and the lack of guidelines that can assure the safety of such complex systems. Furthermore, experts agreed that the introduction of new standards affects requirements by, for example, increasing documentation. Safety analysis is affected by demands such as the reuse of hardware and lack of formal documentation. Another challenge is concerned with the effects that removing the human driver has on safety analysis methods and the design of functions that are in direct contact with the driver. Yet another challenge is not knowing how to handle some aspects of complexity and the lack of methods to deal with increased complexity. Furthermore, ensuring safety, considering the level of complexity that autonomy introduces in the development process is also challenging. Furthermore, regarding challenges related to standards, safety analysis methods, and complexity/complexity handling, different viewpoints were identified between industrial experts or academia and industry. Furthermore, Paper A discusses the implications of these viewpoints regarding these challenges.

One contribution of this paper is identifying different viewpoints within the expert community considering the challenges discussed regarding the introduction of AVs in the automotive industry. Two different viewpoints were identified considering the first challenge. (1) Aligning safety analysis processes with standards benefits the development process. It is a way of having safe and reliable AVs with well-known behaviors, a shared and updated methodology for handling them, and safety analysis methods with increased quality. (2) Standards are just checklists that provide evidence for legal obligations. Instead, having a good safety culture is what is essential. Considering the second challenge, two perspectives were also identified. (1) Experts in academia suggested the need for novel safety and hazard analysis methods. (2) Some experts in the automotive industry believe that there is no need for new hazard analysis methods; others see collaboration within different research projects as the key to providing insights on updated or new safety methods. Furthermore, two different viewpoints were also identified regarding complexity-related challenges. (1) New techniques and methods are needed. (2) Increased complexity can be handled by using the existing methods frequently and rigorously, and by collaboration across the organization. Another contribution stems from analyzing these viewpoints and suggesting possible solutions. There is a gap between academia and industry. Therefore, academic research should consider the industrial context of the research, and industry should support academic research. Challenges related to introducing autonomy affect engineering methods but also the roles and structures of organizations. Collaborative research between different automotive companies can solve or mitigate this problem. Given the different perspectives of experts regarding how to address the key issues leading to these changes, they can challenge the need for collaborative research. Furthermore, the automotive industry should address how these challenges affect the core values of the organization.

4.2.2 Paper B

Paper B addresses the problem of trajectory planning and control for a highly automated vehicle in a road traffic scenario where a collision with other vehicles is unavoidable. This paper is motivated by the concept of contingency motion planning, discussed in Subsection 3.1.3, and the recommendation of NHTSA that a highly automated vehicle should have the ability to protect vehicle occupants in many known *pre-crash* situations [41], [197]. Based on these guidelines and the fact that all collisions are not avoidable [2], this paper aims to improve occupant safety and reduce harm to passengers of vehicles in the event of a crash. This goal is achieved by formulating an optimal control problem that takes the automated vehicle (ego vehicle) from an initial position to a set of goal positions. In this formulation, vehicle dynamics limits are represented as costs and constraints of the optimization. By solving the optimization problem, a trajectory library is generated. The collision severity is defined based on how severe the collision is for vehicle occupants in terms of body injuries. During the run-time operation of an AV, the trajectory with the lowest injury severity is considered the optimal trajectory and will be followed by the ego vehicle. The methods/algorithms are developed and evaluated in simulation. The ego vehicle is equipped with the proposed method/algorithm, and one or two other vehicle(s) are present in the surroundings of the ego vehicle.

The first contribution of this paper is the formulation of a motion planning problem for AVs in unavoidable collisions. In this formulation, the decision on where to strike (impact) a vehicle (in terms of front, side, and rear) is based on the injury severity that the impact will most likely cause for the occupants of the struck (impacted) vehicle. The second contribution of this paper is the specific formulation of the trajectory library approach, which is optimization-based and allows for the inclusion of a complex vehicle model, including tire forces and vehicle dynamics constraints. A trade-off between model complexity and computational efficiency is achieved by performing the trajectory generation offline. This paper presents the initial formulation of motion planning and control in unavoidable collisions, where the desired behavior for this concept is verified in simulation.

4.2.3 Paper C

Paper C takes a data-driven approach and extends the problem formulation of Paper B in more detail by using accident data in its modeling. The same optimization problem as Paper B for generating the trajectories for the ego vehicle is applied. The real-time implementation of the problem formulation is extended in Paper C. A cost function that takes three factors into account is defined: the injury severity related to the impact location, being struck, and the relative pre-crash velocity between the vehicles involved in the collision. The accident data is analyzed, and a metric is designed that relates the injury severity of vehicle occupants to the impact location. This metric is then used in the cost function along with the two other factors that prioritize one action/trajectory over the others to achieve the lowest collision severity. The proposed motion planning algorithm is evaluated in several simulation scenarios, including two-vehicle and multi-vehicle collision scenarios.

The main contribution of this paper is a data-driven approach that uses estimations of injury severity for mitigating harm in unavoidable collisions. This method avoids the simplifications and assumptions that may be needed by deductive approaches both during design and run-time. In this paper, a metric based on analyzing accident data is established that provides a detailed relationship between impact location and injury severity of vehicle occupants. This method is integrated with the trajectory library approach presented in Paper B. Including this metric in the cost function of a motion planning algorithm further improves the accuracy in terms of collision severity representation and reduces collision severity. In addition, a method that distinguishes between the striking and the struck vehicle is designed. In this paper, the injury severity is minimized for the impacted/struck vehicle, regardless if it is the ego or the target vehicle. This choice is motivated by having a higher injury severity on the struck vehicle than on the striking vehicle [198].

4.2.4 Paper D

This paper addresses motion planning in unavoidable collisions while considering uncertainty in the state estimations of a target vehicle. A probabilistic CMS is proposed that aims to reduce the injury severity of collisions in these scenarios. The paper addresses activation time and decision-making strategies for a CMS to reduce severity while not increasing collision probability. State-of-the-art methods to estimate collision probability and propagate uncertainty along a trajectory are applied. The injury severity is also estimated along a trajectory based on the data-driven approach of Paper C. The available choices for the ego vehicle are the trajectories from the trajectory library, presented in Paper B and C. The collision probability threshold and the number of trajectories of the ego vehicle are varied. The CMS is activated when the maximum collision probability for the required number of trajectories is equal to or larger than the collision probability threshold, and no trajectory has zero collision probability. Two decision-making strategies are proposed: (a) severity is calculated at the time step that is associated with maximum collision probability, and (b) severity is calculated at the time step when the collision probability threshold is reached. Furthermore, the effect of each decision-making strategy on minimizing collision severity and activation time of a CMS is investigated. A similar investigation is performed for configurable parameters of a CMS such as the prediction horizon for each decision-making strategy. The outcome of the CMS in terms of reducing collision severity is improved when the severity is aligned with maximum collision probability. The evaluation of the proposed methods is conducted in simulation.

The first contribution of this paper is highlighting that there exists a trade-off between reducing collision severity and not causing a collision that is associated with the activation time of a probabilistic CMS. Acting too early is associated with more uncertain decisions, which may at times cause a crash.

Furthermore, it may not be possible to affect or change the severity of collisions by activating the CMS too late. Given that uncertainty affects these timing constraints, the second contribution of this paper is the formulation of a probabilistic CMS with a configurable collision probability threshold for mitigating injury severity in unavoidable collisions. The third contribution of this paper is, highlighting that the outcome of a CMS is affected by the decision-making strategy and configurable parameters of the designed algorithm for the CMS. This is demonstrated regarding the two decision-making strategies discussed in the previous paragraph, and the prediction horizon is chosen as an example to investigate the effects of configurable parameters of CMS.

4.2.5 Paper E

Paper E positions a CRS within four areas of automation studies [199]: decision-making, information acquisition, analysis, and action automation. In this paper, a new decision-making strategy, defined based on collision risk, is proposed. Based on this strategy, the choice of the optimal trajectory is determined based on simultaneous consideration of collision probability and severity. This strategy and the two other strategies (severity at the threshold and least uncertain severity), presented in Paper D, are analyzed and compared both statistically and by qualitative observations. Statistical analysis showed that these decision-making strategies are statistically significantly different regarding how they affect the outcome of collision severity. Furthermore, the effect of the prediction horizon as a configurable parameter of the CRS is also analyzed. A higher and a lower value for the prediction horizon is set for each decision-making strategy. The outcomes in terms of severity values were statistically significantly different considering the lower and the higher value of the prediction horizon for all three decision-making strategies. The results also showed different behaviors given each decision-making strategy. Furthermore, it was identified that a new SSM that takes severity into account is needed, and one such SSM was proposed. In order to identify sources of unobserved heterogeneity and new collision patterns, actions/trajectories and collision configurations of AVs equipped with CRS should be recorded and analyzed.

The first contribution of this paper is highlighting that different decision-making strategies for CRS are statistically significantly different regarding how they affect the outcomes of collisions in terms of severity. The second contribution of Paper E is underlying that one source of unobserved heterogeneity is such decision-making strategies. The third contribution of this paper is proposing a new SSM that is associated with the likelihood that a least severe outcome existed.

4.2.6 Paper F

This paper addresses the inclusion of post-impact trajectories and states of vehicles after an impact as part of the decision-making of a severity minimization motion planner for an AV in unavoidable collisions. For solving a collision, this paper combines a vehicle dynamics model (3DOF and 4DOF), integrated over the short collision duration, with a model that is based on the conservation of momentum, namely Kudlich-Slibar. Given that each model has its strength and weakness, these two models are combined to take advantage of their strengths. The Kudlich-Slibar model can distinguish between sliding and full impacts (non-sliding). A vehicle model with the inclusion of tire forces has shown higher accuracy in predicting post-impact states of the vehicle [200]. Therefore, the Kudlich-Slibar model is applied to solve sliding impacts, and the vehicle model to solve full impacts. A cost function is proposed that considers several factors related to vehicle dynamics. These factors are lateral deviation, heading angle, yaw rate, and side slip angle. The severity of an impact is calculated based on these factors for pre-impact trajectories of the ego vehicle. Furthermore, by adjusting the cost function according to relevant risks, the method can be configured for a different context. Considering that equipping the ego vehicle with active safety systems did not show positive effects in terms of severity reduction on the struck vehicle, as discussed in Subsection 3.4.4, the severity of a collision is minimized for the target (struck) vehicle. The optimal trajectory is the one that has the lowest cost based on post-impact motions. Then, the ego vehicle follows this trajectory. Furthermore, Paper F demonstrates that post-impact motions are sensitive to the set values of collision parameters (contact friction and contact plane) and collision modeling choices.

The first contribution of this paper is a problem formulation that incorporates the post-impact motions of vehicles in the pre-crash decision-making of AVs. With this approach, the severity of an impacted vehicle in relation to secondary crashes, unlike previous research in post-impact motion planning (see Subsection 3.4.4), is incorporated into the problem formulation. Paper F, as the second contribution, presents an investigation of the sensitivity of post-impact motions to collision modeling and its parameters. Such sensitivity analysis and its implications are not addressed in previous research regarding post-impact motion control applications.

Chapter 5

Discussion, Conclusion, and Future Research Directions

This thesis concludes in this chapter by presenting several discussion points, answering the research questions, and providing future research directions.

5.1 Discussion

This section starts with three main discussion points. Firstly, several choices elected in developing the algorithms/methods of the appended papers are discussed in Subsection 5.1.1. These discussions are based on Paper B to E. Secondly, the collaboration between industrial stakeholders for AVs' road safety is discussed, which is based on Paper A and E (Subsection 5.1.2). Thirdly, the choice of the optimal pre-crash trajectory considering the severity of initial impact versus secondary impact is compared in Subsection 5.1.3. This aspect is discussed from the point of view of Paper C and F. Subsequently, discussions on the validity of the results considering the research design presented in Chapter 2 are presented in Subsection 5.1.4. Afterward, the limitations of the performed research are discussed briefly in Subsection 5.1.5. This section concludes by discussing the ethical considerations regarding the general aspect of AVs research and in more detail concerning this thesis (Subsection 5.1.6).

5.1.1 Design Choices

In this subsection, some of the design choices in algorithms/methods of Paper B to E are discussed. This is especially focused on the trajectory library approach followed by a short clarification on the choices made for probabilistic motion planning of Paper D and E.

Motion planning in an unavoidable collision requires a trajectory that minimizes crash severity under tight time constraints. Therefore, an accurate representation of the vehicle model is needed to utilize the full motion capability of the vehicle, e.g., to operate at its limits, and to allow the real vehicle to follow this trajectory. Research has made progress towards reaching this goal by applying optimization methods in real-time [29], [61], [75]. These methods are advantageous in the way that they allow for the incorporation of complex vehicle dynamics models and their constraints [18]. However, an efficient problem formulation such as a quadratic program is needed to solve these problems in real-time [61], [75], [126]. The cost function of a quadratic program is a quadratic function of states and controls, and thus puts restrictions on how the cost function can be formulated. Therefore, using optimization methods in real-time for a severity minimization motion planner is restrictive in terms of formulating the desired behavior.

Conversely, the cost function for sampling-based methods can be formulated with fewer restrictions. These methods are fast and efficient in trajectory generation [201]–[203]. In [202], a method is proposed that uses quintic and quartic polynomials to represent the longitudinal and lateral motions of the vehicle and to generate trajectories. Trajectories are generated online and a cost function is used to evaluate collision-free trajectories. Given the online trajectory generation, computational efficiency is balanced against model accuracy leading to a less detailed vehicle dynamics model representation in polynomials. However, representation of the vehicle dynamics model as polynomials is not well-suited for dynamic maneuvers such as the ones a severity minimization motion planner requires [26]. The accuracy of different vehicle models based on their applications is discussed in Section 3.2.

Therefore, in this thesis to avoid any simplification of the detailed relationship between impact location and injury severity of vehicle occupants, a data-driven approach is chosen to formulate the cost function of a severity minimization motion planner. The trajectory library approach is applied to address vehicle dynamics model accuracy while reducing online computation. A dynamic bicycle model with the inclusion of tire forces is used to generate a set of trajectories offline. During the run-time operation of the AV, the data-driven cost function evaluates the choice of the optimal trajectory.

In the appended papers of this thesis, the computational time of the proposed algorithms/methods is directly not discussed. This is because the focus has been on the behavioral aspects of algorithms/methods, rather than computational. However, the computational aspect, at a high level, is considered by taking the trajectory library approach, which is inherently parallelizable, and for which computational efficiency has been validated and analyzed in previous research [26], [60], [64]. For example, in [26] the longest run-time of a prototype implementation for a scenario is 60 ms. Several assumptions that are similar to [26] such as offline trajectory generation and use of occupancy grid have been made in the developed algorithm/method of Paper B and C. Therefore, the proposed algorithm/method has the capability for real-time applications even considering the differences.

Considering the trajectory library approach, several factors exist that may require discretization in a real-world scenario. For instance, road friction may be different from the assumed value of it in the trajectory library, which may lead to inaccuracies. One can generate separate sets for different values of road friction. However, discretization for each factor or initial conditions of the vehicle or combination of these can potentially lead to the need for large sets of libraries. The way to approach this is to take more computation online by using computation power and the evolution of computers. This design would drastically reduce the need for discretization. Furthermore, one can reduce trajectory sets by performing sensitivity analysis for different variables.

Lastly, the algorithms/methods developed in Paper B and C are extended to incorporate uncertainty in state estimations of surrounding vehicles (Paper D and E). The aim of Paper D and E in probabilistic motion planning in unavoidable collisions is to understand the implications of uncertainty for decision-making and not to propose novel methods to reduce uncertainty. Therefore, the existing state-of-the-art methods are applied to calculate collision probability and incorporate uncertainty in the states of the vehicle. Furthermore, the maneuver intentions of other vehicles, which are relevant for longer time planning, are not included in the uncertainty formulation due to the tight time constraints of unavoidable collisions.

5.1.2 Collaboration between Stakeholders

According to a policy report by NHTSA, highly automated vehicles have great potential to increase road safety and improve their performance by sharing data [204]. NHTSA urges OEMs to create "a plan for sharing its event reconstruction and other relevant data with other entities" [204]. Sharing accident data contributes to the understanding of how a specific accident happened, in which area, and caused by what errors or violations [205]. Therefore, analysis of the data can be used to prevent future accidents by, for instance, improving vision algorithms, redesigning infrastructure, and enacting preventive measures against those who make the violations [205]. Several factors are enablers of data sharing in the automotive industry [206]: willingness to share data, data collection in terms of its quality, frequency, and completeness, and actual usage of data. In addition, it is challenging for manufacturers to analyze large data sets that will be gathered by AVs. Hence, for gathered data to be beneficial for improving safety and understanding AV's performance, issues in regards to data sharing and data analysis must be addressed. Therefore, this leads to large collaborations between different OEMs and other stakeholders. This collaboration from the point of view of Paper A and E is discussed as follows.

Results of Paper E showed the need for the recording of AVs trajectories in all near-crash situations and recording of reconfiguration of collisions in all crash scenarios when an AV is equipped with a CMS/CRS. The recorded data needs to be analyzed to identify unobserved heterogeneity caused by different decision-making strategies of CMS/CRS and their implications and to provide early feedback to engineers. Given that various OEMs can implement different decision-making strategies, collaboration and data sharing between the stakeholders to fully capture the benefits of data gathered by AVs are needed. Similarly, the results of Paper A showed that collaboration between OEMs is a way to address changes that the introduction of full autonomy brings to engineering methods such as safety analysis methods, roles, and structure of organizations in the automotive domain. However, as discussed in Paper A, the need for such collaborations may be challenged by several experts. Following this logic, a collaboration between OEMs for data sharing on near-crash or crash scenarios can also face resistance from experts within the organization. AV manufacturers may not be willing to share accident data due to liability issues, especially for crashes that led to severe injuries or fatalities. For instance, investigations of the case of Toyota's unintended acceleration are discussed in [207]. According to this document, these investigations by experts showed the presence of "bugs [in an electronic throttle control system] that can cause unintended acceleration". Toyota was fined 1.2 billion dollars for "concealing safety defects" [207], but argued against the control system of the crashed vehicles being flawed.

5.1.3 Initial versus Secondary Impact

In Paper C, the choice of the least severe trajectory is directly related to the injury severity of vehicle occupants resulting from the initial impact. This choice is based on a weighted combination of the injury severity related to impact location and the relative pre-impact velocity between the vehicles (see Eq. (2) in Paper C). However, in Paper F this choice is based on the collision severity of secondary impacts and is formulated based on the evolution of vehicles' motions after the initial impact (see Eq. (25) in Paper F). To further understand how the choice of the least severe trajectory is affected by decisions based on initial or secondary impact, an example scenario from Paper F is discussed in this subsection.

A scenario from Paper F (see Figure 5 in Paper F) is considered. In this scenario, a small set of trajectories of the ego vehicle from the trajectory library are considered and are labeled from 1 to 4. The target vehicle is struck by the ego vehicle at three different impact locations when these trajectories are followed by the ego vehicle. The impact location on the target vehicle is *rear-*

seat if trajectory 1 or 2 is followed. It is *rear-compartment* if trajectory 3 is followed, and it is *rear* of the vehicle if trajectory 4 is followed. Paper F, in which the choice of the least severe trajectory is determined based on post-impact states, identifies trajectory 1 as the one with the lowest severity (see Table 1 in Paper F for cost values). As mentioned in the previous paragraph, the choice of the least severe trajectory in Paper C is mainly associated with the injury severity related to impact location. Considering the same scenario (Figure 5 in Paper F) and applying the cost function of Paper C, the impact locations associated with the highest to lowest injury severity are: *rear-compartment*, *rear-seat* and *rear* of vehicle. Therefore, trajectory 4 that leads to a rear impact is associated with the least injury severity, and the ego vehicle follows this trajectory. Therefore, the choice of the optimal trajectory is different if the initial and secondary impacts are investigated separately.

The intention of motion planning in unavoidable collisions is to mitigate the collision severity across the entire accident, i.e., generating an optimal trajectory that reduces the severity of both initial and secondary impacts. One difficulty of doing so is related to when uncertain situations are considered more certain. For instance, if the occurrence of the initial impact is uncertain, it is reasonable to prioritize reducing the injury severity for the initial impact considering that the secondary impact would be even more uncertain since this event occurs further in time. However, if the occurrence of the initial collision is more certain, thus reducing the risk of secondary impact needs to be considered. Furthermore, as discussed in Subsection 5.1.6, AV manufacturers most likely prefer to focus on the initial collision due to liability issues considering that the possibility of secondary impacts is more uncertain.

5.1.4 Validity

In this subsection, the decisions that have been made to improve internal and external validity and the associated challenges for the adopted research methodology, described in Chapter 2, are discussed. Validity is considered during all stages of the research. The discussion on validity is divided into studies that were conducted based on interviews and the ones based on simulations.

Interviews

Paper A is based on interview studies, and thus qualitative methods are used for data collection and analysis (see Subsection 2.2.2 and 2.2.3). For qualitative research, validity is determined based on how accurate the findings are from the viewpoint of the researcher, the participants, and the readers [35]. Several actions were taken through all stages of the research to improve the validity of the results.

The interviews were performed in the presence of an observer with interviewing experience. The observer was knowledgeable within the field and did not gain in any way from the research output. In this way, any existing bias that may come from the interviewer was controlled. This also allowed for consistency in the interviews and provided new perspectives on the responses of the interviewees. The interviews for Paper A were conducted in two phases by two independent researchers. The transcripts of the interviews were also coded by two researchers independently. The results were compared to identify similarities and differences. These approaches lowered the risk of one researcher being biased. Team members within the research group also checked the results of the analysis. Identifying contradictory perspectives in the expert community was also another way that showed the results are realistic and valid. One way that I could have further improved the validity was to gather data for the study from other sources, for instance, by conducting surveys.

The interview questions, recordings, transcripts, coding, and analysis are well-documented to improve reliability. It is also made sure that the interview questions and the process of coding the transcripts are clear. Documents (codebooks) containing codes, their interpretations, and the frequency of each code are also created and are constantly checked and compared with the data. The design of the interviews [47] and their analysis [49] were performed based on the state-of-the-art literature.

In regards to the generalization of the interview studies, [47] argues that the generalization should be more on the side of being able to transfer the gained knowledge from the interviews to other relevant situations and not globally. Furthermore, [47] discusses the concept of "analytical generalization", which is suitable for the interview study of Paper A. This concept rests upon providing a detailed description of the study, the researcher's judgment that the findings are transferable to other situations, and the readers' generalization of it based on the provided description of the case. For the study of Paper A, experts across different organizations are interviewed, and a detailed description of the case is provided. Thus, based on analytical generalization, knowledge gained from Paper A can be generalized to case studies with relevant attributes.

Simulation

Studies in Paper B to F were performed in simulation. Simulation studies have high internal validity because the researcher has control over the parameters of the system. Therefore, the researcher ensures only what is being studied is varied in each simulation run [28] and that the results are not caused by uncontrolled external factors. [208] identified factors that can be a threat to the internal validity of simulation: model simplification that forces a specific outcome, inappropriate experimental design, and data gathered from different contexts. The models used in this thesis are well-established in the literature. The elements of the simulation environment are designed based on the researcher's experience and under the guidance of experts. One source of input data for simulation is real accident data, which is collected and analyzed in collaboration with experts. Vehicle parameters are also inputs for the simulation and are provided based on realistic values for vehicles [131]. Therefore, this research has high internal validity.

External validity is to what extent findings of the study can be generalized to other situations outside the investigated case [38]. However, this only needs to be valid for cases that have similar characteristics and for which the results are relevant [38]. The external validity for the simulation environment relies on being representative in addressing the real studied problem. However, this only needs to be valid for factors that affect the outcome of the study [28]. Therefore, in this thesis, models that are well-established in the literature and within the field are applied. The simulation environment (MATLAB) is well-known within the field of study and is widely used for algorithm development, scenario building, and evaluation. Considering modeling choices, vehicle dynamics and tire models are based on state-of-the-art and are used for many applications in motion planning and control due to their closeness to reality (see Section 3.2). The accuracy of the applied models in simulation is improved depending on the problem being studied or as needed. For instance, in Paper B and C, where the focus is on developing a novel severity mitigation algorithm, a dynamic bicycle model with tire models is applied for the ego vehicle. This is because this vehicle is required to perform dynamic maneuvers in unavoidable collisions. However, surrounding vehicles are modeled with a kinematic bicycle model, which is a reasonable choice given that the surrounding vehicles are not equipped with the proposed systems. In Paper F, where modeling of post-impact motions is considered, vehicle modeling is modified to include higher DOF models or to combine state-of-the-art models. The applied methods to calculate collision probability and model uncertainty are also well-established in the literature. In addition, the selected case has to be appropriate for the aim of the study. The choices of the case study and the unit of analysis are motivated by the importance of the case, availability of data for the case, its application and relevance in the field, and its ability to allow for the evaluation of the case (see Subsection 2.2).

However, simulation studies are exposed to threats to validity. [208] has identified factors that are threats to the external validity of simulations. According to [208], simulation outcomes may differ from the outcomes of empirical observations such as experiments. Furthermore, the simulation may not be generalized to another simulation addressing the same phenomena. In the following paragraphs, these two aspects are discussed concerning this research.

Considering the first aspect, one example that can influence the outcome of the simulation to be somewhat different from the real world is sensor modeling. Modeling sensors, realistically, is difficult to achieve in simulation. In the real world, sensors are susceptible to errors, delays, and environmental factors such as foggy or rainy weather. Therefore, one threat to validity is the assumption of perfect sensor information in regards to the position and velocity of the vehicles. However, uncertainty in trajectory prediction is considered in Paper D and E. Furthermore, a threat lies in the lack of experimental testing with real vehicles. Considering the ethical issues regarding safety that can arise with the experimental work of this research, a detailed investigation is essential before developing the appropriate test setup.

Considering the second aspect, and by defining the phenomena as *collision mitigation in unavoidable collisions*, the outcome of this phenomena from simulation in terms of the least severe trajectory could be affected by the inclusion of factors such as traffic rules, variations in vehicle types and other road scenarios. However, given that the collision is unavoidable, reducing severity has priority over following traffic rules. The unavoidable collision may have been caused by violating the traffic rules in the first place. Nevertheless, this is not easy to ignore in a dense traffic situation. Considering the vehicle type, factors such as mass and height can affect the choice of the least severe impact location and thus the optimal trajectory. Generalization to different scenarios such as highways requires more data and data analysis. For instance, for highway scenarios, analyzing a rear-end crash could be more relevant, and other factors such as PDOF could contribute to severity more than impact location. However, the selected case of intersection scenario can be generalized to other types of junction scenarios considering that the accident data is gathered from junctions in different countries. The limiting aspect is not the method itself, which is not affected by the inclusion of these factors, but the lack of data. Therefore, the method/algorithms of the appended papers can be extended when more data that drives the choice of the least severe trajectory becomes available.

In terms of reliability, from a higher-level perspective, the codes and algorithms/methods are well-documented, and the research results are written in the form of scientific papers. From a lower-level perspective, reliability is considered during different stages of programming and deciding the algorithmic choices. An example can be provided from Paper D, in which for calculating collision probability, a seed is set for random sampling. Thus, others can produce the same sequence of random values, allowing the results to be repeated.

5.1.5 Limitations

This section discusses the limitations of the research performed in this thesis. Some of these limitations are touched upon previously, for instance, as threats to validity in Subsection 5.1.4.

The findings of this study may be limited to the studied case of the road traffic system and other case studies with similar attributes. The results may not be evidence for other cases with different characteristics addressing a different research problem, for instance, accidents in geographical locations with completely different road structures. However, it is emphasized that this is not a limitation of the methods/algorithms of this thesis. Given the availability of data for different geographical locations, the methods/algorithms of this thesis can further be extended to other cases. Regarding the interview studies performed in Paper A, one limitation is that the choices for the interview subjects and topics of the interview questions were mainly focused on technology and processes points of view in the automotive industry. Not all stakeholders, such as lawmakers, were involved in the interview process.

This research concentrates on motion planning in unavoidable collisions considering other moving vehicles. To evaluate the proposed methods/algorithms of this thesis, it is assumed that drivers of other vehicles do not react to unavoidable collisions. In the real world, drivers of surrounding vehicles can perform unpredictable maneuvers. However, what the vehicle can physically execute based on actuator inputs from a human driver under tight time constraints of unavoidable collisions is limited. More data is also needed to understand the behaviors of drivers of CVs while interacting with AVs in critical traffic situations. Thus, these insights can be incorporated into the decision-making of a CMS/CRS in the future. Another assumption is that the trajectory of other vehicles can be predicted accurately by using kinematic vehicle models (Paper B, C, and F). In the real world, the environment of AVs is very uncertain. However, this assumption is motivated by the characteristic of unavoidable collisions, such as proximity of vehicles and a short prediction horizon, which make the application of physics-based models reasonable [18].

In terms of algorithmic design choices, as discussed in Subsection 5.1.1, if the trajectory library is generated based on a value of road friction that is different from the one in the real world, the vehicle may not be able to follow the optimal trajectory accurately. However, algorithmic solutions are discussed in Subsection 5.1.1 for this case. In addition, research has proposed novel ways to calculate road friction ahead of time by fusion of high accuracy local friction estimation and rough camera-based estimations [209]. It should be noted that a CMS/CRS is activated after a collision avoidance system could not avoid a collision. Thus, it can be assumed that this issue is solved before the activation of CMS/CRS and the correct road friction is estimated ahead of time.

5.1.6 Ethical Considerations

Autonomous vehicles are considered as *implicit* ethical agents [210]. One way to incorporate ethics into AVs is to create algorithms that implicitly promote ethical behavior or constrain their actions to avoid unethical outcomes [211]. One of the most discussed ethical considerations for AVs is known as the *trolley problem*. This problem is formulated in several ways however all address the same ethical issue. One example presented in [211] is as follows: "an autonomous car is barreling down on five persons, and cannot stop in time to save them. The only way to save them is to swerve and crash into an obstacle, but the passenger of the car would then die. What should the car do?" [211] argues that such black and white situations are only suitable for addressing ethical issues for public awareness, and their lack of realism may make engineers disregard such issues. Others have argued that ethical decision-making for AVs is not about whose life should be sacrificed in favor of others but more about who is at greater risk [211]. Balancing risk is considered a way of dealing with these ethical issues without basing them on personal characteristics (e.g., age, gender, physical and mental status); rather basing them on objective features [212]. This view is in line with the data-driven approach applied in Paper C, where risk is related to the impact location of the vehicle, and the choice of the least severe impact location is driven by the statistical likelihood of harm without directly considering personal characteristics. However, given that characteristics such as age or gender can affect the severity level imposed on vehicle occupants, considering their biomechanics, they will be incorporated into decision-making strategies of AVs in relation to impact location. It is important to note that the choice of the least severe impact location would not solely be based upon, for instance, age (child versus adult); it is rather considered concerning the impact location. For instance, if a specific impact location is more severe considering an age group, this aspect should be considered while choosing the least severe impact location.

In addition, "reliable judgments are the result of learning, which can be implicit, with corrective feedback" [213]. This feedback can result from own personal experiences, behaviors of others, or actual historical cases that are similar to the situation [214]. Therefore, ethics in the context of AVs and specifically for motion planning in unavoidable collisions should be addressed through more realistic scenarios. This thesis discusses this concept based on the arguments presented in [215]. First, the trolley problem is a very different decision-making problem than the problem of algorithm development for AVs in accident scenarios. For instance, in the trolley problem, fast decision-making is put upon one person/agent and has to be made on the spot. However, for AVs, the most important decisions such as behaviors of AVs during an accident are programmed beforehand and during the planning stage. In addition, the decision is made by several stakeholders and not just one person/agent. Similarly, it was discussed in Paper A that several stakeholders and experts are involved in the different aspects of decision-making for AVs, from method development to roles of safety experts and engineers within the organizations. Second, for algorithmic decisions of AVs, the decision of how to program AVs must also incorporate legal and moral responsibilities. In unavoidable collisions, who would be liable and what they will be accountable for should be addressed. These aspects are disregarded in the trolley problem.

Third, one of the major critiques of the trolley problem is that consequences of actions have definite outcomes. In the real world, actions have uncertain results. Therefore, considering motion planning for AVs in an unavoidable collision, several sources of uncertainty exist. Predicting the trajectory, velocity, and mass of other vehicles which can affect the severity is uncertain. Information about the environment, for instance, road geometry and road friction, is needed and can affect the decision-making of an AV. However, data gathered by sensors are not perfect and are only estimates. Considering vehicle occupants or pedestrians, several factors such as age, gender, and seat-belt use can affect their survivability. Therefore, similar to [28], ethics of algorithm development for motion planning in an unavoidable collision is related to the problem of decision-making under uncertainty and estimations of severity related to these decisions. This aspect, which is not discussed often regarding the ethics of AVs, is addressed in Paper D and E. It was shown in Paper D that for an AV equipped with a CMS/CRS with a configurable probability threshold, an example scenario existed when activating these systems too early led to a collision that was possibly avoidable if the probability threshold was configured for higher values. Furthermore, considering the same example scenario, the results of Paper E showed that the decision-making strategy influenced the outcome. For instance, based on two of the decision-making strategies a collision occurred that could have been avoided. However, based on the third decision-making strategy, no collision occurred. In addition, due to uncertainty, situations were identified where the crash took place at a different point in time than predicted.

Still, others have proposed strategies for regulating moral issues related to AVs. For instance, [216] proposed a three-phase strategy.[1] The first phase focuses on generally agreed principles and safety metrics that minimize the effects of a crash. The second phase addresses using machine learning to study human decisions across many real-world scenarios and to understand accurate and ethical choices while following the decided rules of the first phase. However, this phase itself is affected by how detailed and beneficial the gathered data is and the presence of unobserved heterogeneity. Therefore, one possible outcome is AV learning ethics that were not intended [216]. The third phase is that AVs express their decisions in natural language that is understandable to humans. However, the decision-making of AVs can be somewhat different from humans. For example, as presented in Paper D, for an AV equipped with a CRS/CMS, a detailed comparison of probability and severity can be calculated while such calculations are beyond the capabilities of humans, especially under tight time

[1]More details on each phase and the associated challenges can be found in [216].

constraints. Therefore, communication between AVs and human drivers or learning from human behavior in many critical traffic situations may not always be applicable and not contribute to the decision-making of AVs.

Furthermore, other factors such as unintentional discrimination or biases in algorithm development [217], and privacy in terms of the type of data gathered by AVs must also be addressed.

As a concluding remark on the ethics of motion planning for AVs in unavoidable collisions, an ethical question is raised concerning minimizing severity across the entire accident scenario. This concept is related to Paper F and refers to reducing the severity of an impact for both the initial and the secondary collision. The question is concerned with any ethical issues associated with *not* reducing collision severity for both the initial and the secondary impact if it is physically possible. A hypothetical scenario is defined to address this concern. In this scenario, passengers of the vehicle are affected both from the initial and the secondary impact. It is further assumed that the secondary impact results in a higher severity value for passengers than the initial impact. Assuming that AV manufacturers are liable for AV accidents, would they be willing to incorporate a decision-making strategy that generates a pre-crash maneuver based on reducing the injury severity of the secondary impact instead of only the initial impact, even though that would be less severe for vehicle occupants? AV manufacturers would most likely base the decision-making strategy on the initial impact and would not want to be liable for the secondary crash, which is further into the future and more uncertain. In addition, as shown in both Paper A and E, several stakeholders such as OEMs, traffic management, and experts in academia must collaborate for the successful and safe deployment of AVs. Therefore, assuming research and analysis of crash data show the possibility of improving the severity of accidents across the entire accident scenario by incorporating secondary impacts, new safety regulations may be required. However, this requires a significant reduction in the uncertainty of unavoidable collisions.

5.2 Conclusion

In this section, the research questions that are formulated in Subsection 1.2.2 are answered.

RQ1:

Which are the most important factors that industrial stakeholders in the automotive industry must consider to allow for the introduction of fully automated vehicles?

This question is answered concerning the summary and contributions of Paper A provided in Subsection 4.2.1.

One aspect to consider is introducing safety-related standards effectively. Standards can lead to massive transitions in companies regarding, for instance, the need for different and more expert knowledge, more documentation, and process automation. Given the two distinctive perspectives identified during the interviews, this transition can be natural or met with resistance in different parts of the organization. Therefore, the automotive industry must find ways to address this transition, which in the latter case may require legal or market demand.

There exists a gap between academia and industry concerning how the need for new safety analysis techniques and the challenge that autonomy brings to these methods is perceived. To address this challenge, new methods developed by academia should be applicable in the industrial context. In addition, the industry needs to find solutions for supporting and integrating new research and engineering techniques. Interview analysis showed that safety analysis is performed by domain experts such as engineers, while safety experts are mentors and reviewers of the safety analysis. Furthermore, engineers focus on outcomes and consider new methods beneficial if they provide better results and reduce their workload. Therefore, these methods should be evaluated regarding the degree of support they bring to producing results while reducing workload. In addition, the consequent changes should be introduced gradually, and engineers should be involved in the decision-making.

Furthermore, results showed that even if methods and technology do not change, the introduction of autonomous systems can affect the roles of safety experts. They could still be mentors or can take over the entire safety process. In addition, removing the human driver brings changes to the safety methods. Hence, organizations should prepare to hire experts with specific knowledge in the field. An alternative to these changes is collaborative research and sharing of gained knowledge between different organizations. Therefore, organizations should also prepare for such changes or collaborations. However, considering the need for such collaborations can be questioned by some experts, automotive companies may need new venues where innovative and unbiased ideas can be discussed. In addition, they should also address the effects of these challenges on the core values of organizations.

RQ2:

Which are the most important factors to consider in the problem formulation of motion planning and control for an AV for minimizing collision severity in unavoidable collision scenarios?

To answer this research question, which highlights research gaps (a) to

(i) presented in Subsection 3.4.5, several factors that are highly important for severity minimization motion planning in unavoidable collisions are identified and presented in Subsection 4.1.1. These factors are united by a motion planning framework presented in Subsection 4.1.2. More research is likely needed considering the growing research and development of AVs. Therefore, this thesis does not claim the completeness of the identified factors. Nevertheless, the proposed framework is valid and a step forward toward research in severity minimization motion planning. In addition, characteristics of motion planning in critical situations provided in [28] can be an inspiration for research related to motion planning in unavoidable collisions. For example, adaptability of vehicle dynamics parameters to the changes in the environment, for instance, road friction can be incorporated in motion planning in unavoidable collisions. This aspect is considered for future research.

RQ3:

If uncertainty is to be considered in the state estimation of surrounding vehicles, what is the effect of it on decision-making strategies of collision mitigation/reconfiguration systems (CMSs/CRSs) of an AV?

This research question highlights research gaps (b) to (d) presented in Subsection 3.4.5. A CMS/CRS has to make a well-timed decision that reduces collision severity. These decisions are: when to act and which actions to pursue. All of these decisions are affected by uncertainty. Considering the activation time, acting too early increases the likelihood of collisions and possibly leads to a collision that otherwise could be avoidable. By contrast, if a CMS/CRS is activated too late, the decision is more certain but provides the vehicle with fewer possibilities or less diversity among the choice of trajectories. Then, it may not be possible to affect or change the severity of collisions. The activation time can be operationalized by defining a threshold for when an uncertain outcome is to be treated as certain. Paper D investigates this by varying a collision probability threshold and the required number of actions/trajectories reaching this threshold. When enough trajectories have a large enough probability, the collision is considered unavoidable. Two behaviors were identified for which the severity increased. (1) acting too late, requiring all trajectories to reach the highest set value for probability threshold, and (2) too early activation leading to a collision. For (1), a lower severity action existed if the CMS/CRS was activated earlier. For (2), a later activation showed that the collision was avoidable.

Decision-making for severity minimization regarding which actions to pursue is also affected by uncertainty. In the design of CMS/CRS, a collision is considered unavoidable when the required number of actions/trajectories have reached the collision probability threshold, and no trajectory has zero collision probability. If it is predicted that the collision occurs at a specific point in time (t_c) along a trajectory, this should imply that the severity at t_c should be representative of the actual severity. However, due to uncertainty, the actual collision could happen before or after t_c.

Furthermore, three decision-making strategies are proposed and investigated in Paper D and E: (a) severity at the threshold, (b) least uncertain severity and (c) equal parts uncertainty and severity. These strategies are visualized in Paper E. Regarding (a), the severity is estimated at the time step where the probability threshold is crossed. Regarding (b), severity is calculated at the point in time with the least uncertainty. Therefore, even though the threshold for collision probability is potentially reached at another time step, the collision severity is calculated at the time step with the maximum collision probability. Regarding (c), equal weights are considered for the severity and uncertainty. In this strategy, collision risk along each trajectory is calculated as the product of collision severity and probability. Subsequently, an action/trajectory with the lowest collision risk is determined for the ego vehicle to follow. It was shown qualitatively in Paper D and E and quantitatively in Paper E that these strategies are significantly different regarding their effects on severity outcomes.

RQ4:

Considering RQ3, which are the most important factors that industrial stakeholders in the automotive industry must consider to allow for the introduction of collision mitigation/reconfiguration systems (CMSs/CRSs)?

This research question highlights research gaps (e) and (f) presented in Subsection 3.4.5. According to the response of RQ3, different decision-making strategies for AVs equipped with a CMS/CRS can have different outcomes in reducing the severity, and their interactions with other road users, e.g., human drivers. Paper E identifies three important factors for industrial stakeholders to consider.

(1) The first one consists of two aspects: (a) the difference between the estimated time of an unavoidable collision, predicted by CMS/CRS, and the actual time it became unavoidable, and (b) the difference between the estimated time and severity of a collision predicted by CMS/CRS, and the actual time and severity of the collision. This factor is related to the need for a new SSM that considers severity for analyzing AV safety equipped with CMS/CRS. Paper E proposes an SSM related to the likelihood that a less severe outcome existed.

(2) All actions/trajectories of AV near-collisions should be recorded by road infrastructure that allows for storing large data sets. In addition, to identify similar collision scenarios that involve a specific mitigation function, e.g., CMS/CRS, statistical tools are needed to analyze post-crash data. This process allows engineers to identify heterogeneity resulting from CMS/CRS. This need

is related to the presence of unobserved heterogeneity that can arise as a result of introducing new automation in AV. Paper E identifies algorithmic differences as an example of factors that are difficult to observe. These differences could be the decision-making strategies themselves or small variations in the configurable parameters of each decision-making strategy.

(3) There is a need to record the configurations of collisions to identify potential missed factors that can affect the collision severity. This is currently needed due to the lack of data on novel automation, and the fact that the introduction of CMS/CRS may change the distribution of accident types or create new collision patterns. For instance, a CMS/CRS that chooses one impact location to be struck over the other to reduce the severity can make another crash type such as rear-end more frequent.

RQ5:

If a motion planner should attempt to minimize severity across an entire accident scenario, which are the necessary components for post-impact motion planning and control?

Reducing severity for vehicle occupants across the entire accident scenario can be considered in two steps: The first step is to decide on a pre-crash action that minimizes the injury severity resulting from the initial impact. The second step is performing a pre-crash action that reduces the severity of a secondary crash. This research question focuses on the latter step and highlights research gaps (g) to (i) presented in Subsection 3.4.5. Paper F identified several aspects that need consideration for reducing the severity of secondary impacts. (1) The choice of a pre-crash action/trajectory to reach the lowest severity is influenced by how a collision is modeled in terms of the choice of the model and the set values for parameters of the model, e.g., contact friction. Therefore, an accurate representation of these choices is necessary. (2) To identify an action/trajectory that leads to the lowest severity, factors that contribute to severity should be identified, and a relationship between severity and these factors needs to be established. (3) Severity minimization should not be limited to the occupants of ego (own) vehicle; it should also address the safety of other vehicles involved in the collision.

In regards to (1), a collision model based on the conservation of momentum is combined with a vehicle model that is integrated over the short collision duration. Previous research has shown that the former model (Kudlich-Slibar) can distinguish between sliding and full-impacts, while the latter has higher accuracy in calculating post-impact states due to the inclusion of tire forces. Regarding (2), several vehicle states, including lateral deviation, heading angle, yaw rate, and side slip angle, and their evolution after an impact contribute to the severity of secondary crashes. A weighted combination of these factors defines a cost function in Paper F, which can be configured for different contexts. How each factor is modeled in the cost function is discussed in Paper F. For instance, the larger the lateral deviation, the higher the risk of exposing the vehicle to secondary impacts. In regards to (3), equipping the ego vehicle with vehicle dynamics and control systems does not have positive effects on the target vehicle (see Subsection 3.4.4). In addition, it is not always possible to reduce the severity of secondary impacts for both vehicles involved because the optimal trajectory for the ego vehicle is not necessarily the optimal one for the target vehicle (Table 1 in Paper F). Paper F makes this decision in favor of the target vehicle.

5.3 Future Research Directions

Pre-crash motion planning in unavoidable collisions is addressed in this thesis through the characteristics that were defined in Subsection 4.1.1, the identified research gaps (a) to (i) presented in Subsection 3.4.5, the contributions described in Subsection 1.2.3, by answering the research questions in Section 5.2, and through the appended papers. Future research can focus on both investigations of methods to further develop and evaluate the identified characteristics and also explore new ones.

Motion planning in unavoidable collisions has common characteristics with motion planning in critical situations, presented in [28]. In [28], the aim is to avoid collisions by fully utilizing the vehicle dynamics capabilities. Therefore, a strong connection exists to combine the research presented in this thesis and the one in [28]. In this case, avoiding a collision by exploiting the full physical potential of the vehicle would be the initial step, and if a crash is unavoidable, the next step is to minimize the severity of the collision. More research on the implementation aspects of this combination is needed, for instance, to understand when to stop focusing on collision avoidance and start focusing on collision mitigation. In addition, motion planning in critical situations has addressed a method of trajectory generation that can adapt to dynamically changing environments, e.g., road friction [218]. In this way, the trajectories are generated online from the current initial state of the vehicle by using the Graphics Processing Unit (GPU). If time constraints of an unavoidable collision allow and with the advancement in computation power, future research should investigate this way of generating trajectories for motion planning in unavoidable collisions.

As discussed in Subsection 3.3.1, other crash factors can also affect the severity of collisions, for instance, vehicle type or PDOF. A detailed relationship between injury severity, impact location, and PDOF was derived for this thesis as mentioned in Subsection 2.2.3. However, this detailed relationship was limited by the lack of data. Thus, the results are not included in this thesis and the appended papers. The data-driven approach of this thesis allows for the inclusion of these factors when more data becomes available. Therefore, another research direction is to incorporate other crash factors into the cost function of a severity minimization motion planner without adding more complexity. In addition, the evaluation of the methods/algorithms developed for this thesis should be extended to include other road scenarios, and severity minimization for vulnerable road users such as pedestrians and cyclists should also be considered.

Future research should include the conceptualization of a method that can simultaneously consider the injury severity of occupants involved in the initial collision and the severity of secondary impacts. The output of this method would be an action that minimizes severity across the entire accident scenario. However, as discussed in Subsection 5.1.3, this is challenging due to uncertainty and liability issues related to secondary impacts and requires further investigations. A more straightforward extension of severity minimization for secondary collisions can be to extend the investigated case to scenarios in which turning maneuvers of other vehicles are considered.

Lastly, a way forward is to extend the evaluations of the methods/algorithms of this thesis to experimental testing on a real vehicle. The ability of the real vehicle to achieve the lowest collision severity by following the desired trajectory should be investigated. Developing the experimental environment and setup requires further investigations due to issues related to safety, cost, and regulations. A more sophisticated simulation setup may be the answer before experimenting on the real vehicle.

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Appended Papers